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DOCTORAL THESIS

A Comprehensive Analysis of Efficiency in the Tasmanian Salmon Industry

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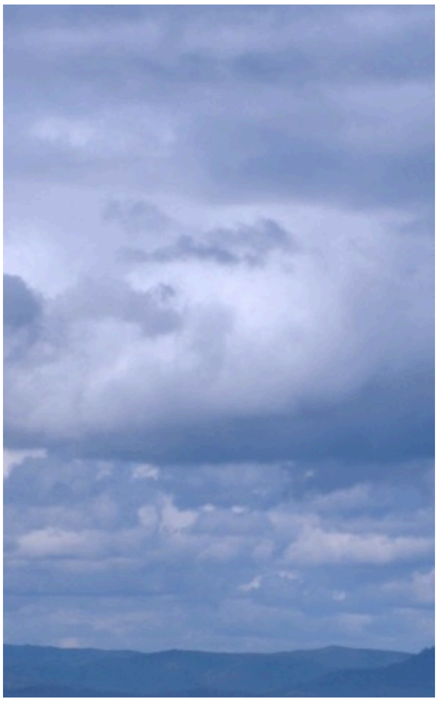

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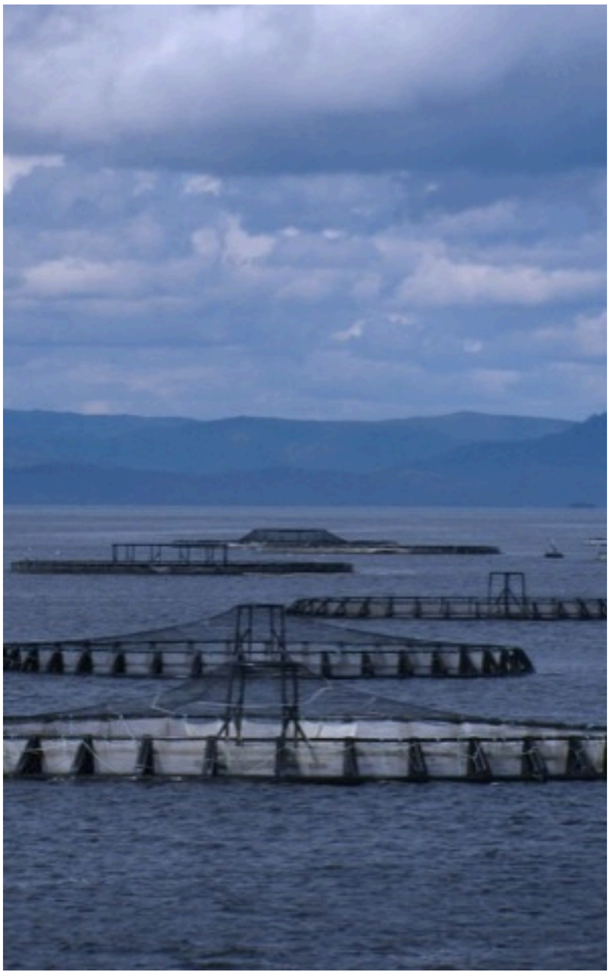

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Abstract

Food producers are under increasing pressure to provide for a growing population that is demanding good quality, nutritious foods. At the same time, they face significant supply-side constraints as the ecological support systems required to produce food are pushed to the limit and the cost of inputs reach record highs. To overcome these challenges producers will need to develop innovative solutions to improve the productive efficiency of the global food system. This research brings together three diverse yet interrelated disciplines – environment, nutrition and economics - under the universal banner of sustainability science in search of a reliable and comparable measure of eco-efficiency that will help drive the food system towards a more sustainable future.

The Tasmanian salmon industry is used as a case study to identify the benefits and limitations of feed conversion ratio and the various measures of forage fish dependency that are currently used to assess the productive efficiency of aquaculture production. Life cycle assessment is identified as being a suitable compliment, with practical suggestions made regarding how this framework could be altered to make it reliable and comparable when assessing food production systems. Comparisons between this research and other similar studies highlight a number of issues that need further attention to enable LCA is to be used as an assessment tool.

The benefit of undertaking such a comprehensive assessment is that food producers and the organisations that regulate/accredit them are able to identify where to direct their efforts to improve the efficiency of production. This will not only help to ensure the businesses within the food system are more aware and accountable for the outcomes of their decisions, but it will also help to bridge the growing gap between supply and demand for food in the future.

Declaration

This thesis is submitted to Bond University in fulfillment of the requirements of the degree of *Doctor of Philosophy.* This thesis represents my own original work towards this research degree and contains no material which has been previously submitted for a degree or diploma at this University or any other institution, except where due acknowledgement is made.

Amelia White

20th September, 2013

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Acronyms

AA	Amino acids
ABD	Abiotic resource depletion
ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
ACMF	Australian Chicken Meat Federation
ADC	Acidification potential
AFIA	American Feed Industry Association
AGD	Amoebic Gill Disease
ALA	Alpha-linoleic acid
ALCA	Attributional life cycle assessment
ALCAS	Australian Life Cycle Assessment Society
ANF	Anti-nutritional factors
APAP	Association of Peruvian Anchovy Producers
ARA	Arachidonic acid
ARA	Australian Rendering Association
ASC	Aquaculture Stewardship Council
ASX	Australian Stock Exchange
AVPMA	Australian Pesticides and Veterinary Medicines Authority
BAP	Best Aquaculture Practice
bFRC	Biological feed conversion ratio
BRU	Biotic resource use
CED	Cumulative energy demand
CH_4	Methane
CLCA	Consequential life cycle assessment
CML	Institute of Environmental Sciences (Dutch)
CO_2-e	Carbon dioxide equivalent
CSD	Commission on Sustainable Development

CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAFF	Department of Agriculture, Fisheries and Forestry
DCCEE	Department of Climate Change and Energy Efficiency
DEDTA	Department of Economic Development, Tourism and the Arts
DEFRA	Department of Environment, Food and Rural Affairs
DHA	Decosahexaenoic acid
DNA	Deoxyribonucleic acid
DPI	Department of Primary Industries
DPIPWE	Department Primary Industries and Water and the Environment
EAA	Essential amino acid
EAFI	Ethical Aquatic Food Index
EDF	Environmental Defense Fund
EF	Emissions factor
EFA	Essential fatty acid
eFCR	Economic feed conversion ration
EIO-LCA	Economic input-output life cycle assessment
EIS	Environmental Impact Statement
EMPCA	Environmental Management and Pollution Control Act
EMS	Environmental Management System
EPA	Eicosapentaenoic acid
EPA	Environmental Protection Agency
EUT	Eutrophication
FA	Fatty acid
FAO	Food and Agriculture Organisation
FCR	Feed conversion ratio
FEFAC	European Compound Feed Manufacturers' Federation
FFDR	Forage fish dependency ratio
FHU	Fish Health Unit
FIFO	Fish in, fish out

FM	Fishmeal
FMFOP	Fishmeal and fish oil products
FO	Fish oil
FRDC	Fisheries Research and Development Corporation
FU	Functional unit
GFC	Global financial crisis
GHG	Greenhouse gas
GM	Genetically modified
GWP	Global warming potential
HAC	Huon Aquaculture
HOG	Head on gutted
HTP	Human toxicity potential
IEA	International Energy Agency
IFFO	International Fishmeal and Fish oil Organisation
IFIF	International Feed Industry Federation
IOA	Input-output analysis
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment (analysis)
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCPUFA	Long chain polyunsaturated fatty acid
LMRMA	Living Marine Resource Management Act
LUPA	Land Use Planning Approvals Act
MFA	Material flow analysis
MFDP	Marine Farming Development Plans
MFPA	Marine Farming Planning Act
MIC	Marine Inspector and Cleaner
MODR	Marine oil dependency ratio

MPDR	Marine protein dependency ratio
MSC	Marine Stewardship Council
MTP	Marine toxicity potential
MUFA	Monounsaturated fatty acid
NGO	Non-government organisation
n-3	Omega-3
n-6	Omega-6
N_2O	Nitrous oxide
NPI	National Pollutants Inventory
NPP	Net primary production
NGGI	National Greenhouse Gas Inventory
NIR	National Inventory Report
OECD	Organisation for Economic Cooperation and Development
PO_4-eq	Phosphate equivalent
POM	Poultry offal meal
PUFA	Polyunsaturated fatty acid
RFE	Reduction fish equivalent
RIRDC	Rural Industries Research and Development Corporation
RLO	Rickettsial-like organism
SAD	Salmon Aquaculture Dialogue
SCFA	Short chain fatty acid
SCO	Single celled organism
SEAT	Sustaining Ethical Aquatic Trade
SETAC	Society for Environmental Toxicology and Chemistry
SFA	Saturated fatty acid
SPC	Sustainable production and consumption
SPC	Secretariat of the Pacific Community
TAFI	Tasmanian Aquaculture and Fisheries Institute
TSC	The Sustainability Consortium

TSGA	Tasmanian Salmonid Growers Association
TSIC	Tasmanian Seafood Industry Council
UFA	Unsaturated fatty acid
UN	United Nations
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
UTAS	University of Tasmania
VLCFA	Very long chain fatty acid
WBCSD	World Business Council for Sustainable Development
WCED	World Commission on Environment and Development
WMA	Water Management Authority
WPCO	Western Central Pacific Ocean
WRI	World Resource Institute
WSSD	World Summit for Sustainable Development
WWF	World Wildlife Fund

Chapter 1: Sustainable Production and Consumption in the Modern Food System

1.1 The Modern Food System

Humans have had more of an impact on the natural environment in the past 50 years than in the rest of human history (World Resource Institute, 2005). This coincides with a period of time in which energy, mainly in the form of non-renewable fossil fuels became readily available through advances in extraction technologies (Pfeiffer, 2006). What is arguably the most influential change that occurred during this time is the widespread adoption of a series of inventions that transformed the food system from one that utilized renewable energy sources and the earth's natural cycles, to an industrial one that relied heavily on energy and nutrients derived from non-renewable sources. This industrialization of the food system commenced in the 1800s when Britain heralded in the *Agricultural Revolution* (Standage, 2010). Over the century that followed, farm work became increasingly mechanized, which together with advances in chemical and transport technologies led to a marked increase in food production (Lang and Heasman, 2004). Of particular importance was Fritz Haber's discovery in 1909 of the process that transformed non-reactive nitrogen gas from the atmosphere into ammonia, the key ingredient in synthetic fertilisers. The subsequent commercialization of this process 20 years later by Carl Bosch allowed farmers to increase yields and utilize marginal lands, which saw a further increase in productivity. The widespread use of synthetic fertilisers marked the beginning of the *Green Revolution* (Pfeiffer, 2006), which started in the 1950s and had a major impact in the 1960s.

This revolution was shaped by a number of scientific and economic reforms that were born out of the widespread devastation that followed the Great Depression. During this period, leaders from major industrialized nations collectively embraced the principles of capitalism in a concerted effort to rebuild the global economy (Stiglitz, 2009). In the scientific community, this period saw revolutionary discoveries in the field of genetics that enabled agronomists to selectively breed staple crops, in particular wheat and rice to produce higher yielding cultivars. At the same time, farmers increased the quantity of non-renewable, energy intensive inputs such as synthetic fertilisers, pesticides, and fuel, as well as irrigation which required fossil-fuel derived energy to pump water to the fields. As technologies became more advanced and fossil fuels, in particular oil, remained relatively inexpensive, the costs of inputs continued to decline relative to labour costs in the developed world (Southgate et al., 2007). As a result, human metabolic energy was increasingly replaced with energy-intensive equipment and chemical inputs (Canning, 2010).

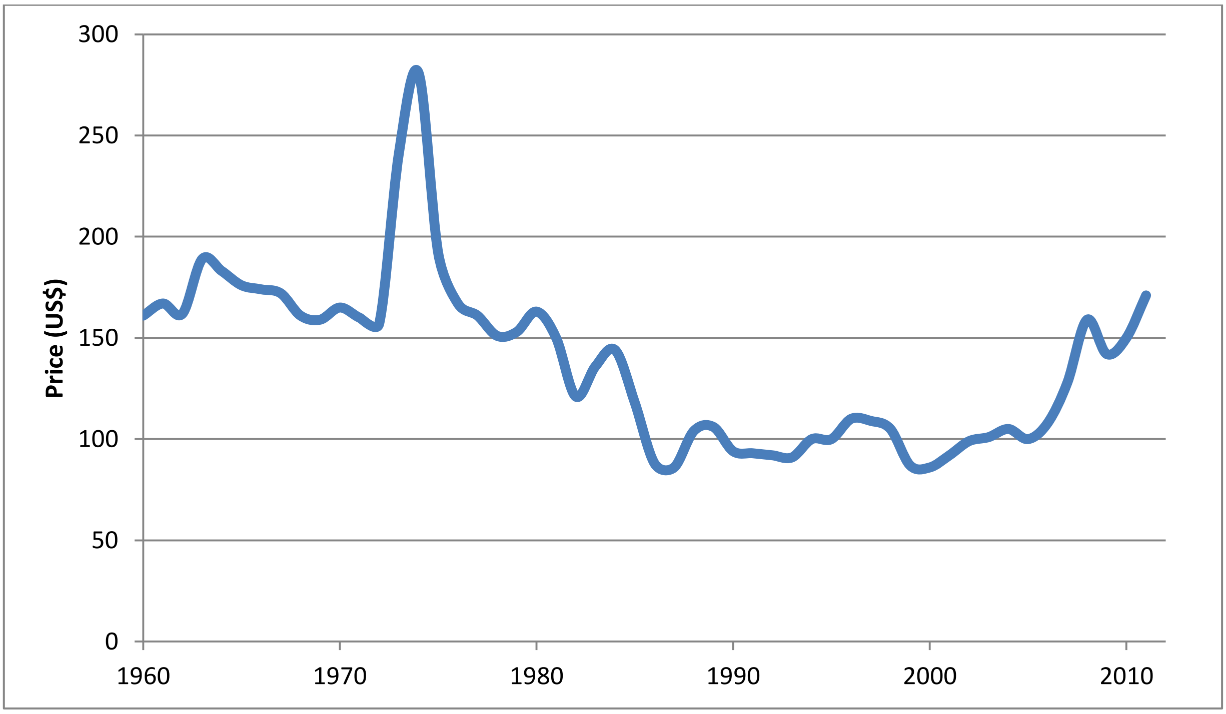
The increase in the availability of crops enabled significant amounts to be diverted to the production of animal feeds that were formulated to match the specific nutritional requirements of the animal under production. This shift from traditional forage diets, together with the intensification and mechanization of the livestock industry led to a marked increase in the availability of animal protein for human consumption (FAO, 2004). According to the records provided by the Food and Agriculture Organisation (FAO) the collective impact of this has been a 60 percent increase in per capita consumption of terrestrial animal proteins, from 19.6g/day in 1961 to 31.2g/day in 2009 (FAO, 2012a). This level of production requires an estimated 780 million tonnes of feeds (Tacon, 2010) that utilize significant amounts of raw materials, with estimates that around 50% of global grain production (Keyzer et al, 2005), 97% of soymeal (Steinfeld et al., 2006) and over 25% of the total wild fish catch (Naylor et al., 2009) are used to produce animal feeds.

In the second half of the 20th century the *Blue Revolution* took hold of the seafood industry, which saw aquaculture transform what was the last remaining hunter-gatherer system (Sachs, 2007). This sector has developed rapidly over the past three decades, making it the fastest growing food production sector in the world, with an average annual growth rate of 8% between 1990 and 2007 compared with 1% for beef production, 2% for pork and 5% for poultry (Brown, 2009). This was in response to the growing awareness of the collapse of key wild capture fisheries and the recognition that an alternative was needed if supply of seafood was to keep up with growing demand (De Silva et al., 2011). This goal has been achieved, with global seafood consumption increasing from 9.9kg per capita in the 1960s to 18.4kg in 2009, of which approximately half comes from aquaculture (FAO, 2012b). Like the livestock industry, one of the key drivers of growth in this sector has been the widespread use of formulated aquafeeds (Tacon, 2010). However unlike the agricultural revolution, it is the East not the West that is leading the way, with China alone accounting for 61.4% of global production in terms of volume, and a further 30% from other Asian countries such as Thailand, Vietnam and Japan (FAO, 2012b).

The sum of the aforementioned developments and the associated productivity gains have permitted food supply to outpace worldwide population growth, and in doing so defy the doomsday predictions of the Reverend Thomas Malthus. In his influential book, *An Essay on the Principle of Population* (1798), Malthus predicted that population growth would exceed the productive capacity of the earth, and as a result societies would collapse. These fears resurfaced in the 20th century with neo-Malthusians such as Paul Ehrlich (1968), The Club of Rome (1972) and Lester Brown (1995). While recognizing the finite nature of the resources that are essential for industrialised food production, and the limits of the natural sinks required to assimilate wastes generated, they failed to factor into their assumptions and models the power of human ingenuity and scientific innovation (Southgate et al., 2007). Advancements in the methods used to produce, process and store foods has seen the availability of calories increase from 2,411 kilocalories (kcal)/person/day in 1969/1971 to 2,789 kcal/person/day in 1999/2001 (Alexandratos, 2006). This was accompanied by a 20 percent decline in the prevalence of undernourishment in a majority of developing regions, with the exception of Sub-Saharan Africa and parts of South East Asia (Schmidhuber & Shetty, 2005).

This unprecedented productivity growth has been accompanied by changes in the price of food, which as shown in Figure 1 have followed a downward trend over the past half a century. Over this time there have been a series of peaks and troughs that are common in agricultural markets due to their exposure to the vagaries of nature, with two significant spikes occurring in the early 1970s and a second more recent one in 2008. Although adverse weather played a role in these events, what set them apart from other peaks was the interaction with broader macroeconomic forces that led to high inflation, together with shocks that occurred to the price of energy (Rapsomanikis, 2009). The latest spike has attracted widespread concern, for unlike the 1970s crisis that saw prices return to normal within two years, it is now four years after the 2008 spike and the price of food has stayed well above the historic trend (HLPE, 2011). This has put the Malthusian predictions back in the spotlight, as many question the ability of the food system to cope with changes to the underlying economic fundamentals by which it is governed. These will be discussed below.

Figure 1: Food Price Index, US$ 1960 to 2011 (2005=100)

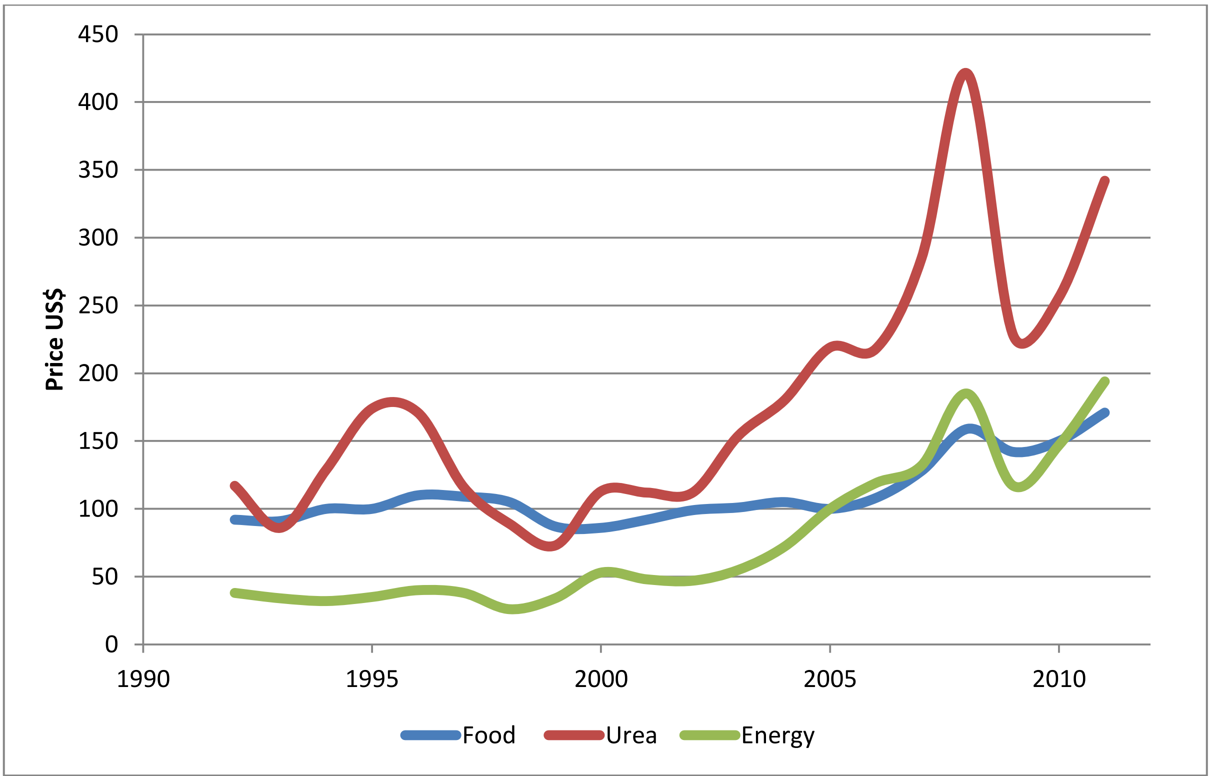


Source: World Bank, 2012a

1.2 Factors Affecting Supply and Demand for Food

As discussed above, the wide spread industrialization of food production in the 20th century has created a system that is heavily reliant on the availability of industrial energy. Therefore it is not surprising that it is a key determinant of the price of food, as well as many of the other inputs required in its production. This includes the nitrogenous fertilisers that are also fundamental to achieving high agricultural yields (Rapsomanikis, 2009). The interaction between these three materials over the time leading up to the 2008 spike can be seen in Figure 2, whereby the price of energy and urea fertiliser began to increase around 2003-4, followed by a rise in the price of food shortly after. The driving factor behind this was the increase in demand for energy and other commodities to fuel the industrialization occurring in parts of the developing world (Helbling, 2012). Following the peak in 2008 there was a sudden fall in the price of all three commodities as the global financial crisis (GFC) took hold and stunted economic growth.

Figure 2: Relative price of key commodities and food 1960-2011 (2005=100)



Source: World Bank, 2012a; IMF, 2012a

Due to the quick recovery of the developing nations that were driving the commodities boom, together with a series of political issues in the oil producing nations of the Middle East, it did not take long for the price of energy to recover. Not surprisingly it took the price of food with it, resulting in another peak in 2011. This upward trend is expected to continue with the International Energy Agency (IEA) predicting that demand for energy will increase by a further 30 percent between 2010 and 2035 (2011a). Given the finite nature of energy resources, it is expected that the additional demand will be accompanied by a rise in price, with a barrel of oil expected to increase to around US$120 (2010 dollars), and the price of food to follow suit (EIA, 2011a).

The prices of energy and food have become further integrated as a result of the growing demand for grain and oilseed to make biofuels. As the price of oil increases biofuels become a more commercially viable alternative, resulting in an increase in production. This is accompanied by a rise in demand for food crops such as corn and sugar that are used as the basis of ethanol production, as well as canola and palm oil for biodiesel. Between 2000 and 2010 the quantity of biofuels produced has increased from 16 billion litres to over 100 billion litres, largely driven by government support in the form of mandates and subsidies that exceeded 8 billion US dollars (IEA, 2012). This growth was particularly rapid over the period leading up to the 2008 spike, with production increasing by 80 percent from 2005 to 2008 (OECD/FAO, 2011). Whilst this is estimated to have accounted for 50 percent of the overall increase in cereals use during this period (*ibid*), the extent to which this additional demand influenced food prices is highly debated, with estimates ranging from three to 30 percent (Mueller et al., 2011). Although the search is underway to find alternative feedstocks such as algae or cellulosic materials, there is currently no commercially viable large-scale production of them. As such, in the short term food crops are expected to remain the primary source of materials used to produce an estimated 155 billion litres of ethanol and 42 billion litres of biodiesel by 2020, which is predicted to place upward pressure on the price of food (OECD/FAO, 2011).

There are also concerns regarding the availability of other resources that are fundamental to food production such as clean water, fertile soils and a stable climate. Unlike energy and fertilisers, the majority of these ecological goods and services are not valued in the market (Daly & Farley, 2004). Therefore the price of food does not reflect their relative scarcity and as a result, modern food production systems have tended to over or misuse these goods and services that nature provides free of charge. This has not only affected the health of the natural environment, it has also limited the future productive capacity of the food system (OECD/FAO, 2011). For example, the widespread use of nitrogenous fertilisers over the past half a century has led to a doubling in the availability of biologically reactive nitrogen (Pelletier, 2010) of which only 10 to 20 percent is actually consumed by humans (INI 2004). The remainder is lost to the natural environment through processes such as the direct leaching of the fertilisers to groundwater, as well as the excretion of nitrogenous compounds contained in the metabolic by-products of animals bred for human consumption. One of the major impacts of this has been the eutrophication of freshwater and coastal ecosystems that has resulted in the formation of dead zones in the ocean where fish and aquatic species are unable to survive (WRI, 2005). Poor agricultural practices have also been identified as one of the key causes of the desertification of farmlands that threatens the livelihoods of around 1.5 billion people that rely on these as a source of food (UNCCD, 2011). Similar concerns are held for the 130 million Chinese and 175 million Indians being fed from the over pumping of water from aquifers on the North China and Indo-Gangetic Plains that are beginning to show signs of depletion (Brown, 2011).

Desertification and declining water availability are amongst the numerous challenges that climate change is predicted to impose on food production systems, the extent of which will vary significantly between regions (IPCC, 2007). For example, droughts that are characteristic of the African and Australian continents are set to intensify, along with other regions in America and Asia (Dai, 2011). This is in contrast to more temperate regions such as Russia and Canada that could potentially experience improved crop yield due to the lengthening of their growing season (Schmidhuber & Tubiello, 2007). Similar trends are expected for fisheries as a result of shifts in ocean currents and water temperatures, with data showing that changes are already occurring in the distribution and productivity of a number of fish species (Brander, 2007). Rising water temperatures are also expected to change the spatial distribution of key aquaculture species (De Silva & Soto, 2009). The increase in the frequency and severity of weather events such as heat waves and floods are expected to affect food production from both terrestrial and aquatic food systems, as well as cause damage to vital supply chain infrastructure (Gregory et al., 2005).

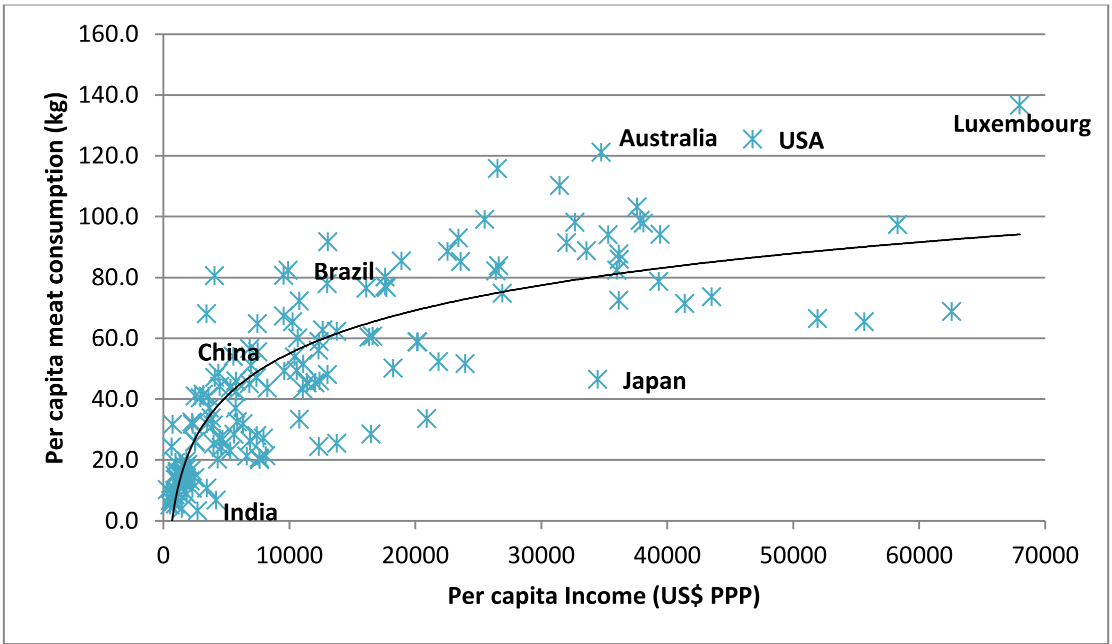
The implications of these supply-side constraints are intensified by the fact that the food system is predicted to have an additional two billion buyers in the market by 2050, as global population grows to around nine billion (McMichael, 2001). This is expected to be an urban phenomenon that is driven by a combination of rural migration and natural growth that is concentrated in cities and towns throughout the developing world (Satterthwaite, 2007). Asia is expected to be the source of a significant amount of this growth, with an additional 1.4 billion people expected to inhabit urban areas by 2050, along with 0.9 billion from Africa and 0.2 billion from Latin America (DESA, 2012). On the one hand, urbanization offers significant benefits through improving access to education and employment opportunities that can increase disposable income, reduce the risk of food insecurity and ultimately lead to a decline in fertility rates (Bloom & Khanna, 2007). However, participation in the urban workforce is generally accompanied by a more sedentary lifestyle, with the additional hours spent at work leading to a preference for convenience foods and snacks (Steinfeld et al., 2006). Such foods are more readily available in the urban environment due to the existence of marketing and distribution infrastructure that enables people to gain access to foods from around the globe (Schmidhuber & Shetty, 2005).

These shifts in diet and lifestyle that are characteristic of urbanization, along with the declining price of food have been driving factors behind the nutrition transition that has spread throughout the world (Popkin et al., 2001). The first stage of this is characterized by an expansion effect whereby there is an increase in the supply of nutritional energy that is generally derived from cheaper foodstuffs of vegetable origin (Kearney, 2010). This is followed by the substitution effect whereby the energy supply stays the same, but the source of calories shifts from carbohydrate rich staples to vegetable oils, sugar and animal proteins (Schmidhuber & Shetty, 2005). Whilst the increased availability of food has helped to address the prevalence of under nutrition, many of these foods are high in refined sugars, fats and salt that act to increase the palatability and shelf life of relatively cheap, bland foods. This makes them cheaper than highly perishable, health promoting fresh fruits, vegetables and lean animal proteins (Monsivais et al., 2010). Therefore these nutrient-poor foods have become the energy source of choice for urban dwellers from low socio-economic backgrounds in both the developed and the developing world. The result has been a marked increase in the prevalence of lifestyle diseases such as cardiovascular disease, obesity and diabetes that were traditionally only seen in affluent societies where people could afford to over consume (WHO, 2005). This has led to an emergence of a new type of malnutrition, which paradoxically is associated with overconsumption rather than the conventional form, which is caused by inadequate food intake (World Bank, 2006). In fact it is now common to see both forms occurring side-by-side in the developing world in a phenomenon known as the double burden of malnutrition (Schmidhuber & Shetty, 2005).

In contrast, animal proteins tend to be more expensive therefore an increase in their consumption is generally associated with a rise in income. The extent to which income affects people's purchasing behaviour is referred to as income elasticity of demand, which varies depending on whether the product is considered to be normal or inferior. Goods that are normal are those that experience an increase in demand if the real income of an individual or economy increases, for example fruits, vegetables and animal proteins. In contrast, the demand for goods that are inferior declines as income increases since people are able to afford a more superior good. This refers to foods such as starchy tubers, grains and pulses that form the basis of the diets of the world's poorest people. This relationship between income and food consumption is noticeable in the dietary shifts that are accompanying the growth in the middle class in parts of Asia and South America (Holmes, 2010). This is particularly evident in China where real GDP per capita has risen from around USD$72 in 1962 to USD$1,209 in 2011 (World Bank, 2012b). This has been accompanied by a ten-fold drop in the consumption of pulses from 30g/capita/day in 1963 to 3g/capita/day in 2003 that was offset by a nine-fold increase in egg and meat, together with a dramatic fourteen-fold increase in dairy over the same time period (Kearney, 2010).

Although the recent growth in demand for animal proteins has predominantly come from emerging nations, it is that from wealthier, developed countries that accounts for the majority of overall consumption. This can be seen in Figure 3, with countries such as Australia and the USA consuming 30 percent more meat that Brazil and more than double that of China. It is also evident from this graph that although income cannot explain the level of meat consumption in all instances (often due to cultural or religious reasons), the general trend reflects the relationship discussed above. The reason for this is that animal proteins are generally more expensive than plant-based foods on account of the additional resources required in their production. For example, the production of one kilogram meat requires between two and ten times the amount of energy than the equivalent amount of grains (Naylor, 1996). This not only increases the costs of production, but also the associated environmental impacts. This is of particular relevance to animals that are fed on grains, for as little as ten percent of the energy contained in the grains is converted to edible protein due to the inefficiency of feed conversion (Holmes, 2010). When viewed from a food security perspective this is even more controversial as these grains could be fed directly to humans and in doing so allow more people to be fed with fewer resources. The implications of reducing products sourced from ruminant animals is even greater due to the significant contribution these animals make global GHG emissions (IPCC, 2007).

Figure 3: Per capita income and meat consumption, 2007



Source: World Bank, 2012a; FAO, 2012a

The increase in purchasing power of consumers from emerging economies has also resulted in aggregate demand being less responsive to changes in the price of food. This is best explained by Engels law, which states that as income grows the percentage spent on food decreases and as a result demand becomes increasingly inelastic. As such, the recent spikes in the price of food did little to curb demand from middle class consumers who spend as little as ten percent of their weekly budget on food (Brown, 2011). This was certainly not the case for the rural poor for whom food constitutes over half of their household budget, with the 2008 crisis undoing much of the achievements that have been made over the past decade in regards to the prevalence of undernourishment in these populations (FAO, 2011a). Despite the recent downgrades to global economic growth forecast by the International Monetary Fund (IMF), high employment and solid consumption in the emerging nations such as China and India are predicted to see these economies maintain a healthy level of growth of around seven percent (IMF, 2012b). The subsequent rise in middle class consumers is predicted to contribute to higher and more volatile food prices in the future, the impacts of which are to be felt by the poor (OECD/FAO, 2011).

This need to balance the needs and wants of human development with the biophysical constraints of the earth is not unique to the food industry. But rather it is at the root of a number of issues that society currently faces including climate change, energy security, and water availability. In seeking solutions there is an increasing interest from governments and NGOs, as well as the business community to adopt the principles of sustainable production and consumption (SPC).

1.3 Sustainable Production and Consumption of Food

The concept of SPC was developed following the release of the *Brundtland Report* in 1987 (WCED, 1987). This report, commissioned by the UN World Commission on Environment and Development (WCED) first introduced the concept of sustainable development, defined as *'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'* (WCED, 1987, p.27). This document helped to shape the international agenda and attitudes towards the idea that social and economic development must occur within the limits of the natural environment. These three components – the economy, the environment and society became known as the three pillars of sustainable development.

At the Rio Earth Summit in 1992 it was formally agreed that the ongoing damage being done to the global environment was caused by unsustainable patterns of production and consumption (UN, 1997). A formal definition of SPC was developed at a subsequent UN meeting in 1994, referred to as the Oslo Roundtable on Sustainable Production and Consumption. According to this definition SPC is *"the use of services and related products which respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the lifecycle of the service or product so as not to jeopardise the needs of future generations."* (Norwegian Ministry of the Environment (1994). The commitments made at Rio were renewed at the World Summit for Sustainable Development (WSSD) held in Johannesburg, 2002 where world leaders once again recognised the need to eliminate unsustainable production and consumption, classing it as one of three key objectives of sustainable development (Barber, 2005). To deal with these issues, delegates called for the development of a 10-year framework to help shift society towards SPC patterns, which was assigned to the Marrakech Task Force. In 2010 the final draft of the 10 year framework was released however it has failed to get acceptance at the subsequent rounds of the intergovernmental Commission on Sustainable Development (CSD), including the most recent one that took place at the Rio +20 Summit in 2012.

It is not only the 10-year framework that has failed, but rather the very concept of SPC has been unsuccessful in infiltrating society at the scale required to drive change. In recognition of the need to put these theories of sustainability into action, there has been a growing movement of scientists from a diverse range of disciplines working towards putting the goals of sustainable development into practice. In this emerging field, known as *Sustainability Science* researchers are working alongside practitioners to produce solutions to environmental problems by combining theoretical and applied sciences (Clark and Dickson, 2003). The primary focus of this discipline is to better understand the individual components and complex dynamics that arise from interactions between human and environmental systems through the integration of a diverse range of disciplines (Clarke, 2007). Such an approach has inherent appeal when seeking to understand and resolve problems related to the production and consumption of food. This is because the associated support systems are characterized by complexity and there is need for multi-disciplinary input to ensure the best outcome for society (Walter-Toewns and Lang, 2000; Lang and Heasman, 2009).

Based on the discussions presented above, this research is proposing that a comprehensive assessment of the food system requires the input of three key disciplines. Firstly, economics which is a social science that aims to understand how scarce resources should be allocated to satisfy unlimited human wants. Next is environmental science, which is the study of the raw materials and nutrients that are transformed within the food system, and the biophysical limits within which this takes place. And finally, nutritional science which is concerned with the utilisation of the energy and nutrients created by the food system to provide nourishment.

1.4 Measuring Efficiency from a Sustainability Science Perspective

The above-mentioned issues facing the food system were the focus of a meeting of high-level experts at the United Nations (UN) *How to Feed the World in 2050* conference in October 2009. They concluded that the productivity of the food system will need to increase by 70 percent by 2050 to meet growing demand, whilst simultaneously reducing the usage of water, agri-chemicals and fuel (FAO, 2009). In other words, the food system will need to become more efficient in its use of resources. This form of efficiency, referred to by economists as productive efficiency, is concerned with finding the optimal combination of inputs required to produce maximum output for minimum cost. However, many of the ecosystem goods and services required to produce of food, along with the associated environmental and social health outcomes are not valued in the market (Daly and Farley, 2004). Therefore this measure has failed to provide an accurate yardstick by which to measure progress (Lang and Heasman, 2004). If the food system is to meet the coming challenges, the inputs and outputs used to calculate the productive efficiency must change to shift the focus towards eco-efficiency, whereby the goal is to produce the most value with the least environmental impact (WBCSD, n.d). In this context, the ultimate aim for food producers would be to maximise the use of nutrients, energy and value to produce food for human consumption.

The concept of eco-efficiency was introduced by the Business Council for Sustainable Development (now known as the World Business Council for Sustainable Development (WBCSD)), in their joint publication with Stephan Schmidheiny in 1992. It is essentially a management philosophy that encourages business to search for environmental improvements that yield parallel economic benefits (WBCSD, n.d). Although the concept itself is simple, in order for it to work in practice there is a need for comparable environmental data that can be used alongside the financials (Kicherer et al., 2007). Without this, businesses are unable to set targets, measure performance and evaluate progress (Verfaillie and Bidwell, 2002). Sturm et al. (2004) specified four characteristics that are essential for an effective eco-efficiency measure:

1. Understandability: able to be interpreted by users
2. Relevance: able to influence users
3. Reliability: free from errors and bias
4. Comparability: ability to benchmark and compare results

There are a range of tools from the sustainability science discipline that provide a suitable framework to assess eco-efficiency, with life cycle assessment (LCA) regarded as one of the most robust and comprehensive (Hall et al., 2011; Shau and Fet, 2008; Ytrestøyl et al., 2011). LCA is a methodological framework used to quantify the environmental impacts that occur over the entire life cycle of a product or service (Rebitzer et al., 2004). Often referred to as a cradle-to-grave analysis, LCA incorporates both upstream and downstream impacts of the production of goods and services. One of the major benefits of LCA is it allows for multiple environmental impacts to be calculated from the same dataset. As such, it is used for a broad range of applications, including the identifying environmental hotspots in a production process, informing product disclosure statements or comparing products and services against others (ISO, 2006a). However, there are a number of methodological issues with LCA that limit its ability to provide a comparable assessment of food production systems (Jeswami et al., 2010; Ayer et al., 2007; Pelletier et al., 2007). This includes the lack of consistency in the selection of the reference unit (functional unit), the scope of the study, the underlying assumptions used and the selection of allocation method (Guinée et al., 2001; Schau and Fet, 2008). Of these, the latter has proven to be the most controversial issues regarding the LCA methodology due to the significant impact it can have on the results obtained (Ayer et al., 2007; Pelletier and Tyedmers, 2011; Weidema, 2003; Curran, 2007; Heijungs and Guine ́e, 2007; Lundie et al., 2007; Ekvall and Finnveden 2001; Guinee et al. 2001).

Allocation refers to the method used to assign the environmental impacts of a production system to different outputs where two or more products or waste streams are created. This is of particular importance to the salmon industry, and other intensive food production systems that are both consumers and producers of significant amounts of by-products. The ISO standards (2006b) provide a hierarchy of three allocation options. However the decision of which to use is ultimately up to the individual practitioner, with the two most commonly used methods being biophysical (mass or energy) and economic. The first of these is seen by some to provide a more biophysically meaningful reflection of the movement of material, energy and emissions through a production system (Pelletier et al., 2009; Pelletier and Tyedmers, 2011). It is also considered to be more reliable for benchmarking purposes, for unlike economic values, these remain relatively stable overtime and place (Winther et al., 2009). However, others argue that this approach is that it fails to recognize the underlying forces that drive production, and in doing so it can over-allocate the environmental burden to the lower value by-products, instead preferring to use the economic value.

This research will endeavor to contribute to the growing body of work in the field of LCA by proposing an alternative approach that incorporates both economic and biophysical allocation methods. It is hypothesized that the modified methodology will enable a more reliable and comparable assessment of food production systems to accompany existing measures of productive efficiency. It is intended that this will assist businesses to make the transition towards eco-efficiency by identifying environmental metrics that can be used alongside financials to set targets, measure performance and evaluate progress. Similarly, this will also provide governments and third party accreditation schemes with metrics by which they can assess and benchmark different production systems as a way to encourage best practice.

1.5 The Tasmanian Salmon Industry

The aquaculture sector offers enormous opportunity to help bridge the gap between supply and demand (Foresight, 2011; Khan et al., 2011). However, it is also recognized that if not managed correctly, aquaculture has the potential to create significant environmental and social externalities (Bostock et al., 2010; The World Bank, 2006). For like all other food commodities, the market price for seafood is predicted to increase due to a combination of increasing demand and the rising costs of production. The implications of this are expected to be significant for the aquaculture sector, with estimates that the cost of these products will increase by as much as 50 percent by the year 2020 relative to the average 2008-2010 price (OECD/FAO, 2011). On one hand the higher market price provides producers with a good incentive to produce more, whilst the higher costs of production make it more difficult for them to do so whilst still making a profit. This creates an incentive to misuse the goods and services that nature provides free of charge, or to reduce the nutritional quality of the fish to keep costs to a minimum. However, if this growth is going to occur sustainably, the industry must address the productive efficiency of their operations to ensure that they are able to deliver a nutritious product at the least environmental and economic cost.

The salmon industry provides an interesting case study as it currently sits at the crossroads of sustainable production and consumption (Tironi et al., 2008). From the consumption perspective the industry is a producer of a highly nutritious food that is widely recommended by nutritionists and health professionals as part of a healthy diet, most notably due to its high omega-3 content. In contrast, from a sustainability perspective the production of salmon is criticized due to concerns regarding issues such as the release of nutrients from the marine farms (Gowen and Bradbury, 1987) and the spreading of disease to wild fish populations (Revie et al., 2009; Hammell et al., 2009; Raynard et al., 2007). It is also attracts attention due to their reliance of wild-capture fisheries as a source of feed ingredients (Naylor et al., 2000; Naylor et al., 2009: Tacon & Metian, 2008), and more recently through their integration with the wider agro-food system as they shift towards more terrestrial feed ingredients (Brown, 2009). Whilst some would argue that given the problems identified earlier, the production of salmon and other high value proteins should not take place at all due to the high resource requirements, the reality is that the market is demanding these products. Instead it is more practical to work towards improving the efficiency of these systems.

Various aspects of salmon production have been assessed in previous LCAs, including comparisons between salmonid (trout) farming and other carnivorous aquaculture species (Aubin et al., 2009) as well as comparisons to proteins derived from wild capture fisheries and terrestrial systems (Ellingsen & Aanondsen, 2006; Winther et al., 2009). Other authors compared the performance of on-farm technologies (Ayer and Tyedmers, 2009), or different feed formulations (Pelletier and Tyedmers, 2007; Papatryphon et al., 2004; Boissy et al., 2011). One study (Ytrestøyl et al., 2011) looked specifically at the performance of the Norwegian salmon industry, whist another (Pelletier et al., 2009) compared the performance of the four largest salmon industries in Norway, Scotland, Canada and Chile.

The one thing that was consistent amongst all studies was that the conclusion that the feeds were the major source of environmental impacts. As such it would seem logical that any attempt to improve the eco-efficiency will require environmental metrics to complement the existing nutritional and economic variables that are used to guide the sourcing of feed ingredients and feed formulation. However, the difference in methodological approach taken by each of these studies results in different conclusions being drawn in regards to which feed ingredients carry the highest environmental impact.

To overcome these issues, this research will examine the LCA methodology and seek to find an alternative way to improve the comparability and reliability of results. To test whether the proposed changes are able to improve the current approach, the Tasmanian salmon industry will be used as a case study for this research. This industry has been chosen for a number of reasons. Firstly, it offers a good opportunity to test the alternative allocation methodology being proposed by this research since it is both a significant producer and consumer of by-products. In regards to consumption, almost 50 percent of the ingredients used in the feeds are by-products from other production systems. This is considerably high compared to the feeds assessed in the above-mentioned LCAs which range from eight to 36 percent. From a production perspective, the industry has recently implemented resource recovery projects to deal with the numerous by-products and wastes that are created during the production and processing of the salmon. Further to this it is a relatively small industry, with just two feed producers supplying majority (85%) of the feeds, five companies that produce and process the salmon, and one that value-adds the by-products. All except one of these are located in close proximity, making the task of collecting accurate primary data more achievable. The data collected in the process of undertaking this analysis will also enable the calculation of other efficiency measures such as feed conversion ratio (FCR) and fish in fish out (FIFO) for which there is not currently an up-to-date industry average published for the Tasmanian industry.

1.5 Research Questions and Objectives

The research questions are formulated as follows:

1. *How can LCA be used to enhance existing efficiency metrics to provide a reliable and comparable assessment of the eco-efficiency of food production systems?*
2. *How does the Tasmanian salmon industry perform when assessed using the proposed methodology?*

Six objectives have been set to guide the research process:

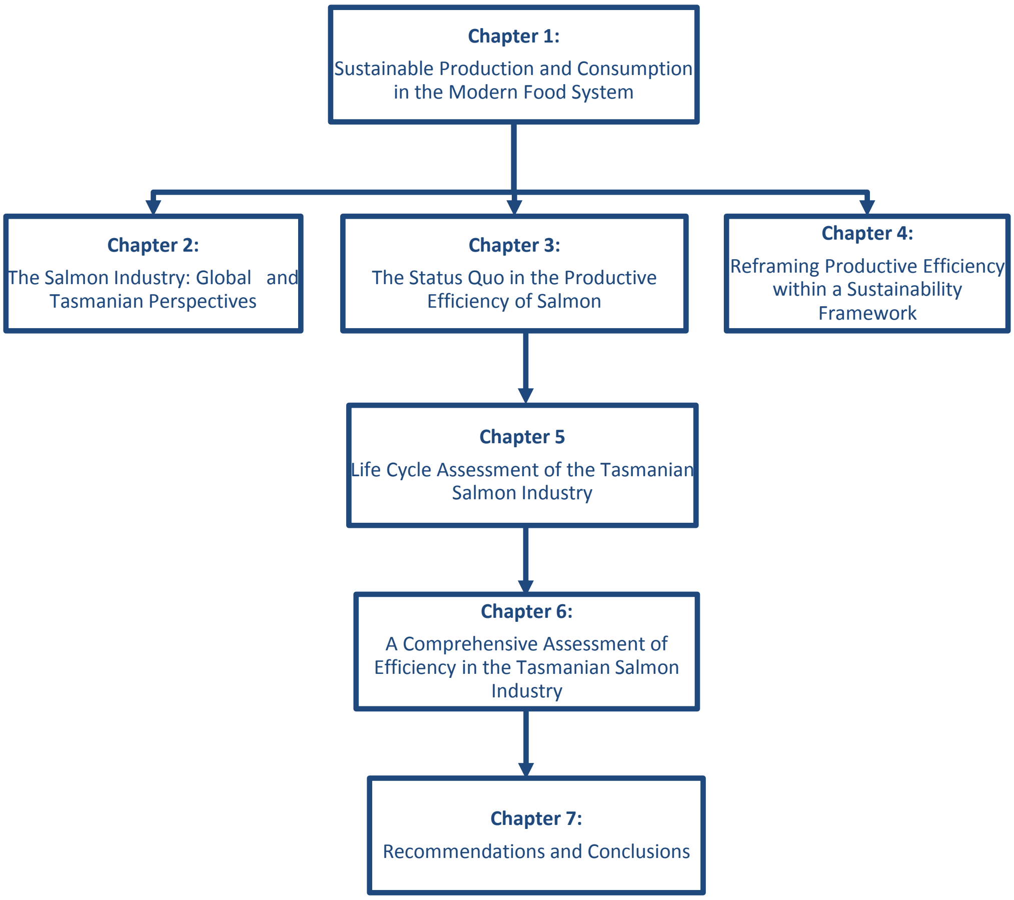
1. *Identify key stakeholders from the Tasmanian salmon industry and the inputs, outputs and processes involved in the associated supply chain (chapter 2)*
2. *Evaluate current measures used to assess the productive efficiency of salmon aquaculture (chapter 3)*
3. *Assess the pros and cons of using LCA as a tool to provide the environmental data required to make an assessment of eco-efficiency (chapter 4)*
4. *Make recommendations as to how the LCA methodology can be modified to provide more reliable and comparable data (chapter 5)*
5. *To assess if the proposed modifications achieve the desired result by applying them to an LCA of the Tasmanian salmon industry*
6. *To make recommendations as to how the Tasmanian salmon industry can improve the eco-efficiency of its operations and the associated supply chain*

This research aims to contribute to the ongoing development of the LCA tool so that it can provide the necessary information to enable well-informed decisions to be made regarding the productive efficiency of food production. The results of the LCA itself will also provide the Tasmanian salmon industry, together with stakeholders from other similar production systems with a better understanding of hotpots in their supply chain and actions that can be taken to minimize these in the future. Similarly, this will assist governments and other organisations that regulate/accredit the aquaculture industry to identify and encourage best practice.

1.6 Outline of Further Chapters

Chapter two will provide a description of the global salmon industry, with a particular focus on the development of the Tasmanian industry and its key stakeholders. Building upon this, chapter three will examine the existing measures of productive efficiency used in the aquaculture industry, as well as the environmental, nutritional and economic factors that have contributed to improvements in these over time. This discussion will be used to highlight the pros and cons of these measures in regards to the issues identified earlier in this chapter. Chapter four will begin with a brief summary of some sustainability measures that could be used to complement those identified in chapter three, with a particular focus on LCA as a suitable tool. This will involve a critique of the important methodological choices involved in the LCA process, with suggestions made as to how these could be addressed to provide results that are more consistent and relevant to assessing food production. Following this, chapter five will provide detailed information regarding the assumptions made for the LCA of the Tasmanian salmon industry along with the associated limitations. A discussion of the results and the implications of these will be undertaken in chapter six, which will then form the basis of the recommendations and conclusions given in chapter seven. The structure of the thesis and the linkages between the chapters is summarized in Figure 4.

Figure 4: Structure of thesis



Chapter 2: The Salmon Industry: Global and Tasmanian Perspectives

2.1 Salmon: King of the Fish

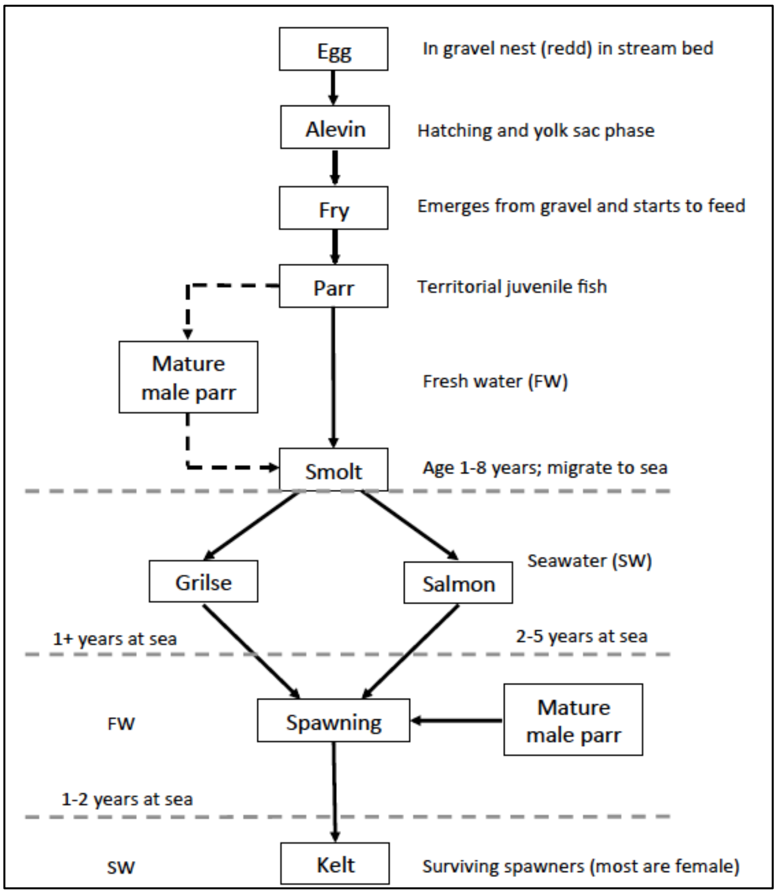
Salmon, together with certain species of trout, charr and whitefish form part of the *Samonidae* family, also referred to as salmonids. They are native to the northern hemisphere, with species originating from both the Atlantic and Pacific Oceans. Atlantic salmon (*Salmo salar*) is indigenous to the North Atlantic Ocean from the Barents Sea in northern Norway and Baltic southward to northern Portugal, around Iceland and southern Greenland as well as along the coasts of Canada and North America (FAO, 2013). This gives rise to three distinct groups; North American, European and Baltic based on the rivers in which reproduction takes place (Fay et al., 2006). Pacific salmon live in the oceans and rivers of western North America and eastern Asia. There are five species of commercially important Pacific salmon; chum (*oncorhynchus keta*); sockeye (*oncorhynchus nerka*); pink salmon (*oncorhynchus gorbuscha*); coho (*oncorhynchus kisutch*); and chinook (*oncorhynchus tshawytscha*), as well as a sixth species, cherry salmon (oncorhynchus masou) that is endemic to Asia (Seafish, 2009).

All species of salmon thrive in colder waters, with the optimum temperature ranges between 4-15^{o}C (Heen, 1993). The southerly aspect of their distribution is therefore limited by the upper limits of their thermal tolerance and a dependence on migration to cold freshwater to complete their breeding cycle (Porter et al., 2002). They are anadromous, migrating between fresh and salt water, with the exception of some landlocked species (Fishresource, 2007). Their lifecycle begins in freshwater, where the female deposits thousands of eggs in gravel at the bottom of rivers, which are immediately fertilized with the milt of a mature male (Laird and Needham, 1988). This generally takes place in autumn, and depending on the temperature of the water, the eggs incubate for around six to twelve weeks before hatching to become alevins. The fish then develop further to become fry, and depending on the species and the environmental conditions, they spend an average of six to 24 months in freshwater before migrating towards brackish waters where the river meets the ocean.

As they make their way, they undergo a series of changes in morphology, physiology and behaviour in a process known as smoltification (Jobling, 2010a). Perhaps the most significant are those that allow them to adjust to varying levels of salt in the water (osmoregulate) and adapt to the marine environment. The timing of this change is triggered by a combination of hormonal and environmental cues; in particular the lengthening of the days and the warming of the water as the transition from winter to spring takes place (McCormick et al., 2002). The variation in daylight is thought to play a role in the release of hormones such as melatonin (Porter et al., 1998) and growth hormone (Björnsson et al., 1994) that have been found to play a role in triggering the smoltification process. Now referred to as *smolts*, they complete their migration to the sea where they grow to maturity before returning to their natal river to spawn, a process that can take between one to five years. The decision of when to migrate back to freshwater is once again driven by endogenous and exogenous cues, with their sense of smell helping them to find the way back to their natal river (Bandoh et al., 2011). Once they reach their final destination, the lifecycle once again begins with the spawning process. Some Atlantic of salmon then return to sea, repeating the above-mentioned cycle to spawn more than once, however all Pacific die after the first spawn.

Salmon are carnivorous, relying on organisms from lower trophic levels to supply essential nutrients and energy. As they move through the various life-cycle stages, their physiological needs vary, with consumption patterns shaped by the inherent vagaries of nature and the availability of natural prey organisms (Jobling, 1993). For the first four to six weeks of life, the yolk sak from the ovum is the sole source of nourishment for the growing alevin. Once this has been consumed, the young fry begin to feed on microscopic life and the decaying bodies of the salmon that have died post spawning. During their time spent in freshwater rivers they shift from eating smaller organisms such as larvae to larger ones such as planktonic crustaceans and insects as the fish mature (Jobling, 2010a). Following smoltification and the migration to seawater, their diets are determined by location and season, with mesopelagic fish, pelagic and crustaceans commonly eaten. Once the sexually mature fish return to freshwater to spawn, they stop eating and rely solely on the fat reserves from their time spent at sea for nourishment. Figure 5 shows the major developmental stages that occur during the lifecycle of Atlantic salmon.

Figure 5 **: Life cycle of Atlantic Salmon**



Source: Jobling, 2010a, pp. 258

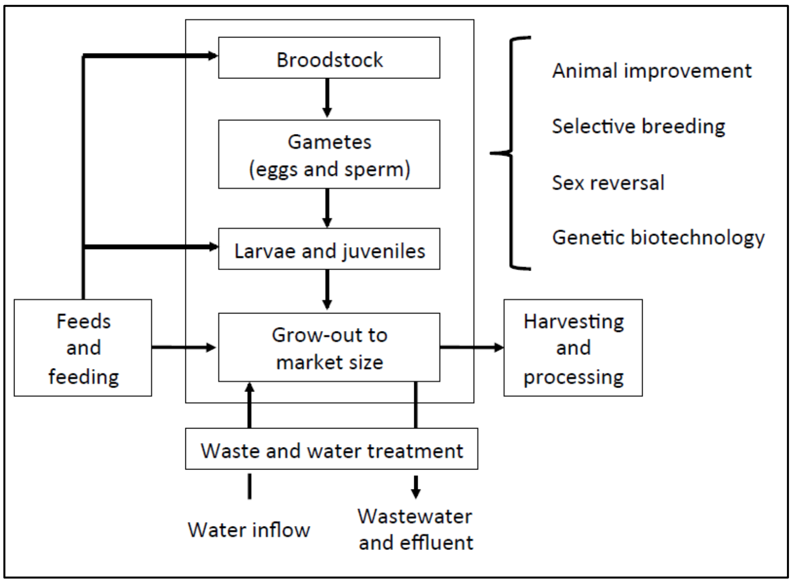
Like many other species, wild salmon populations have been significantly affected by human activities. Overfishing, damming of rivers and the development of other industries such as agriculture and mining have affected habitats and migratory patterns of the species in both the Pacific and Atlantic Oceans (Bjørndal et al., 2003). Today, the Alaskan industry is the major supplier of wild caught salmon, accounting for approximately 35-40 percent of the total annual wild catch in 2009 (Wild Salmon Centre, 2009). The viability of this industry is strong due to its good reputation for sustainable fisheries management, and a natural environment that remains relatively unaffected by human development (Knapp et al., 2007). Of the total 363 thousand tonnes of wild capture salmon caught in Alaskan waters in 2010, three species accounted for 97 percent: pink (50%), sockeye (29%) and chum (18%)(Alaskan Department of Fish and Game, 2010). The remaining wild catch is made up of sockeye and chum species from Russia (25%), chum from Japan (20%)(Wild Salmon Centre, 2009) and a smaller quantity from the remainder of North America (excluding Alaska)(Bjørndal et al., 2003).

Although there is still a strong market for wild capture salmon, in 1997 aquaculture became the number one source of salmon, (Bjørndal et al., 2003) with approximately 71.1 per cent of total supply (by weight) of salmon coming from aquaculture in 2010 (FAO, 2012c). The increase in the availability of farmed salmon on the market has had a significant impact on the value of the wild fisheries, which dropped from $800 million in the 1980s, to less than $300 million between 2000 and 2004, despite catch levels staying fairly constant (Knapp et al., 2007). Further to the economic impacts, the culture of salmon in areas where wild stocks exist is believed to have had an impact on the genetic diversity of the wild populations through the interaction of escapees from salmon farms (Youngson et al., 2003). Ironically, the wild capture industry is heavily reliant on aquaculture, with approximately 30 percent of the world total of 'wild' salmon catch derived from fish that have been spawned, hatched and fed for a few months in hatcheries for the purpose of restocking rivers and creating or enhancing targeted commercial exploitation opportunities (Bjørndal et al., 2003).

2.2 Salmon Aquaculture

Salmon aquaculture is the oldest form of fish-rearing in Europe and North America (Lovell, 2002). The culturing of fish is undertaken for two distinct purposes (Laird and Needham, 1988); the first is partial culture of juveniles for the purpose of re-stocking rivers and lakes to ensure the viability of commercial and recreational fisheries. The second is total culture, where the fish spend their entire life in captivity, with the purpose of meeting demand for table fish. In the case of salmon, both forms of aquaculture are widely practiced, however this research focuses on the latter form. Intensive fish farming involves human intervention in all phases of the production cycle, from broodstock management through to the marketing of the final product (Figure 6). This type of production system closely resembles the business models adapted by terrestrial farmers, commonly known as agri-business.

Figure 6: Overview of the production cycle of farmed fish



Source: Jobling, 2010b, pp.4

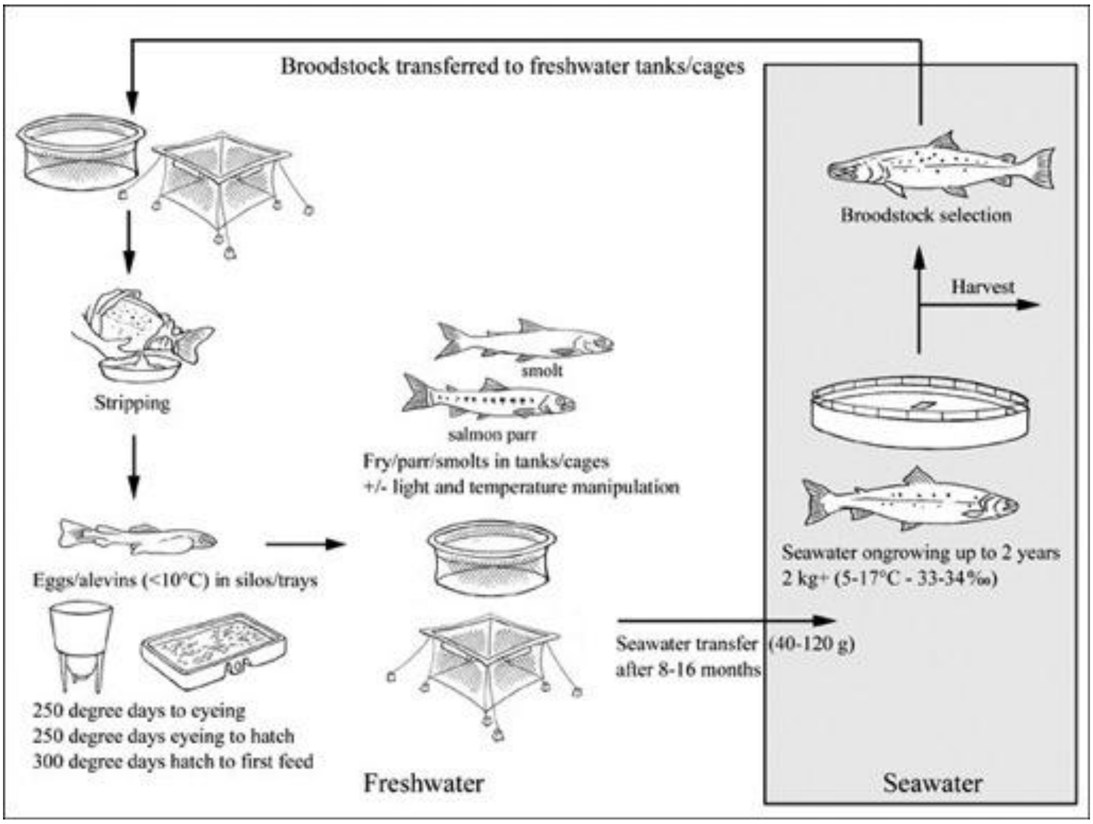
The discovery of the method used to artificially fertilize salmonid eggs is attributed to Prussian Stephan Ludwig Jacobi in 1763 (Araneda et al., 2008). The process was refined over time in hatcheries throughout parts of Europe and North America for the primary purpose of restocking rivers (Knapp et al., 2007). However it was not until the mid 1960s that the culture of Salmonids became commercialized in Norway, later taking off in the 70s and 80s. From a production perspective, the success of the industry was driven by advancements in technology and animal husbandry. This was accompanied by strong demand for the desirable organoleptic qualities of salmon, making it one of the few species that fetched a high enough market price to justify the capital and operating costs associated with aquacultural production (Monahan, 1993). As a result, salmon has grown to become the largest cage aquaculture species by volume and value in the world (FAO,2012a).

Due to the thermal tolerance range of salmon, farming operations are limited to locations between the latitudes of 40^{o} and 70^{o} in both the southern and northern hemisphere, with the exception of the small number of Japanese farms in Honshu (36^{o}) where special husbandry practices have been developed (Monahan, 1993). As well as water temperature, salmon require high levels of oxygen and low levels of pollutants (Araneda et al., 2008), with sheltered environments such as bays, sounds or fjords providing the ideal setting for salmon aquaculture production (Oppedal et al., 2007). Both the Atlantic and Pacific species are used for aquaculture, with Atlantic salmon accounting for greater than 90 percent of global salmon aquaculture production (FAO, 2011b). The dominance of Atlantic salmon is due to a combination of physiological and behavioural characteristics that make them more suitable to intensive culture, such as their ability to adapt to environments outside their natural range (Knapp et al., 2007). Of the six species of Pacific salmon, only two are produced under aquaculture developments in significant volumes, coho and chinook, with the bulk of this occurring in the Canadian and Chilean industries.

The salmon aquaculture process mimics the natural life cycle described above, comprising of a freshwater and saltwater phase. It begins with the selection of breeder fish (broodstock) that exhibit desirable characteristics such as growth rate, disease resistance, maturation and colour (Marine Harvest, 2008). The spawning process takes place in freshwater hatcheries during the autumn months (April in the Australian industry), with the eggs from the females and milt from the males manually 'stripped' from the broodstock by trained handlers. These are then combined in a sterilized container where the fertilization process occurs. The eggs (referred to as green eggs) are left to incubate for around six to 12 weeks, with manipulations of the water temperature to either increase or decrease the speed at which development occurs. This is one of many strategies used throughout the salmon lifecycle that has allowed the industry to meet year round market demand for what is essentially a seasonal product. The next stage is marked by the visible development of an eye, which signals that the eyed eggs can be handled as they are past the fragile stage of the development process.

As in the wild, once hatched the alevins feed on the nutrients contained in their egg sacs for the first few weeks of life. Past this point, their nutritional requirements are met solely by highly sophisticated aquafeeds that are varied throughout their lifecycle to meet their specific requirements at the various stages of development. As the parr grow, they are progressively moved to larger tanks for the duration of their freshwater lives (8-16 months) until they are ready to undergo smoltification. Once this has taken place, the smolts are moved to sea cages or pens that are large, floating mesh structures that are open to the marine environment (WWF, 2011). They begin the saltwater phase of their life in the mildly saline brackish waters, and are then moved further out to sea as they grow. The growth rate of the fish varies significantly depending on the species under cultivation, the water temperature and the availability of food and respiratory gases with the average time taken to reach maturity being 18 months (Oppedal et al., 2011). Fish are harvested when they weigh between 3 and 7kg, although the market preference is for 4-5kg fish (Marine Harvest, 2010). A summary of the salmon aquaculture production process can be seen in Figure 7.

Figure 7: Salmon aquaculture production process



Source: FAO, 2011b

Salmon are widely recognised as being one of the most efficient and successful species under intensive production (Forster, 2002; Gaitlin, 2002), a matter that will be discussed in more detail in chapter three. This is in part due to the inherent biological advantage of being a cold-blooded animal which means less energy is required to regulate body temperature, hence a higher percentage of dietary energy can be converted into muscle mass (Holm et al., 2003). Over the past few decades this natural advantage has been further enhanced through continued investment in the fields of nutrition, genetic selection, disease control, farming and post-harvest processing technology (Johnston et al., 2006). These advancements, together with the adoption of agribusiness models that have proved successful for terrestrial systems have allowed the industry to provide consumers with a consistent, high quality product throughout the year (Otton and Dooley, 2010).

As the industry has developed, the associated economies of scale and improvements in productivity have resulted in a decline in average production costs (Asche, 1999). As supply has increased without a countering increase in demand the global average price dropped in the early 1990s by 21 percent, from $US3,500 per tonne in 1989 to $US2,750 in 1994 (Williams, 2004). As a result, salmon is now able to compete in price with other meats such as chicken, pork and beef (Naylor and Burke, 2005), making what was once considered to be a luxury item a global commodity that is available all year round. Although the volume of salmon produced represents only 2.3 percent of total volume of fisheries production (Marine Harvest, 2010), it accounts for 12 per cent of the total value of internationally traded fishery products, making it one of the most highly traded fish commodities, and the most widely consumed seafood product in the developed world (Naylor and Burke, 2005). Production is concentrated in four countries; Norway, Chile, Scotland and Canada that cumulatively account for around 90 per cent of global production (Table 1).

***Table 1*: Estimated global salmon production, 2010**

Country	'000 tonnes
Norway	928
Chile	246
Scotland	155
Canada	101
Australia	32
New Zealand	13
Others	102
Total	**1,577**

Source: FAO, 2012d

The majority of product is sold fresh (whole, steaks, filleted), frozen and smoked (FAO, 2011b). Japan was traditionally the largest market for salmon, however the EU and USA have overtaken it in recent years (Globefish, 2011), with new markets developing in Central and Eastern Europe, South East Asia, China and South America (Bjørndal et al., 2003).

2.3 The Global Salmon Industry

Norway has the most developed industry, and despite growing competition, it continues to be the largest producer, accounting for around 59 percent of global salmon production in 2010 (FAO, 2012d). What started off as a small industry in the 1960s grew rapidly due to a combination of favourable environmental conditions, the availability of skilled labour, efficient distribution networks (Heen et al., 1993), and strong government support for research and development (Knapp et al., 2007). Atlantic salmon is the sole species cultivated, with production sites spread amongst the many fjords, inlets and islands that are characteristic of the Norwegian coastline (Bjørndal et al., 2003). The salmon industry is an important source of export revenue for Norway, accounting for 90 percent (AUD$4.15 billion) of their total seafood exports in 2009 (Norwegian Ministry of Fisheries and Coastal Affairs, n.d). The majority (70%) of this is sold to local EU markets, ten percent to Asia and eight percent to Russia (Marine Harvest, 2010).

A relaxing of laws relating to farm size and multiple farm ownership that occurred in response to a drop in market price during the 1990s led to significant consolidation in the Norwegian industry, and the emergence of a smaller number of large, vertically integrated businesses. This is recognised as being one of the key factors that has allowed them to remain highly competitive in the global market despite growing competition (Forster, 2002). The industry continues to receive significant government support, although the majority of the recent expansion has been the result of research and development (R&D) funded by the private sector (Knapp et al., 2007). The highly integrated nature of the industry is currently undergoing further change, with many of the larger companies now outsourcing the processing of fish to countries where costs are lower, most notably China for frozen products, and Poland and the Baltics for smoking (Globefish, 2011).

Chile is the world's second largest salmon producer, accounting for 16 percent in 2010, of which approximately half were Pacific salmon, and the other half Atlantic (FAO, 2012d). It stands out from the other ‘big four’ producing nations for a number of reasons. Firstly, it is the only one that is located in the southern hemisphere, and hence, the only one to which salmon is not native. It is also the only developing country that produces salmon at a large scale, which made it initially reliant on foreign investment in the industry. Starting in the early 1980s, it was a relative latecomer to the industry, but then grew rapidly with an annual rate of 42 percent between 1984 and 2004 to overtake Scotland as the second largest producer in 1993 (Knapp et al., 2007). This growth was largely driven by the influx of foreign companies that saw an opportunity to capitalize on the abundance of sheltered coastlines and ideal water temperatures Chile had to offer. In addition to these natural features, the Chilean industry had further competitive advantage due to the easy access to fishmeal for feed, low-cost skilled labor, a favorable regulatory climate and less pressure from environmental groups than the established industries in the northern hemisphere (Hicks 1995). The expansion of the Chilean industry had significant impacts on the global market for salmon, believed to be one of the key reasons for the glut that occurred in the early 2000s (Alaskan Department of Community and Economic Development, 2001). Similar to what happened in Norway, the industry responded to the subsequent drop in price by consolidating to form larger, vertically integrated businesses (UNCTAD, 2006).

Production occurs along the coastline of southern of Chile, with the majority concentrated around Puerto Montt and Chiloé Island, about 1,000 km south of Santiago (Knapp et al., 2007). The industry has played a significant role in the economic development of these regions through the creation of direct and indirect employment opportunities, and the improvement to existing infrastructure and services (UNCTAD, 2006). Since salmon is not a traditional part of the Chilean diet, the majority of production is exported, making it one of the country’s key export commodities. The Atlantic salmon are sold primarily to the USA and to a lesser extent, EU markets, and the coho salmon to the Japanese market (UNCTAD, 2006). Despite predictions that it would overtake Norway as the world’s largest producer, in 2009 Chile suffered a dramatic loss of almost 50 percent of its Atlantic salmon stock as a result of an outbreak of the Infectious Salmon Anaemia (ISA) virus (FAO, 2010). The decline in supply on the global market had a significant impact on the price, which reached record highs in 2010 (Globefish, 2011). The industry is showing positive signs of recovery, with the key representatives of the industry predicting that they will return to full production by 2013 (Globefish, 2011).

The third largest producer is Scotland, accounting for ten percent of global production in 2010 (FAO, 2012d). Salmon farming was set up in the late 1960s by Marine Harvest Ltd, a subsidiary of Unilever in response to the success of the Norwegian industry (Heen, 1993). After years of slow and steady growth, the industry took off in the later half of the 1980s as a result of financial support from European and local investors (Knapp et al., 2007). Production leveled off in the late 1990s following significant setbacks including the outbreak of ISA and the aforementioned glut on world markets. Since this time, expansion in the industry has been limited due to the lack of suitable production sites, with any growth the result of productivity improvements and the consolidation of companies which has seen the industry become tightly concentrated in the hands of a small number of businesses (Bjørndal et al., 2003). Salmon farming takes place at various locations, with the bulk of production concentrated along the west coast where fish thrive in the favourable environmental conditions similar to those found in Norway (Knapp et al., 2007).

Unable to compete with Norway and Chile on price, the Scottish industry has focused on quality rather than quantity, and is one of the major producers with a strong domestic market for its product (Bjørndal et al., 2003). The industry is an important source of export revenue, accounting for 40 percent of the country’s food exports, making it Scotland’s the largest food exporting industry (Scottish Development International, 2011). Aquaculture is also a major source of employment and economic opportunities for many remote, economically vulnerable parts of the country (Bjørndal et al., 2003).

Accounting for approximately six percent of global production in 2010 (FAO, 2012d), Canada is the world’s fourth largest producer. The industry began in the 1970 in British Columbia, later spreading to parts of eastern Canada (Bjørndal et al., 2003).

The industry initially grew quickly along both the east and west coasts with the support of European venture capital funding (Agriculture and Agri-food Canada, 2008). However, the industry was significantly impacted by a moratorium on expansion that was introduced in 1995 in response to conflicts between wild-capture fisheries, and the negative image of the industry amongst environmental and indigenous (First Nation) groups in British Colombia (Knapp et al., 2007). Although the moratorium was lifted in 2002, the industry remains tightly regulated, which limits its ability to reach full productive potential (GSGislason & Associates, 2006).

Today salmon is the largest aquacultural sector in Canada, accounting for 71 percent of total output, with a value of $653 million Canadian dollars (AUD $627m)(Fisheries and Oceans of Canada, 2011). Although originally based on Pacific species (coho and chinook), the Norwegian companies that became involved in the industry during the mid-1980s introduced the Atlantic species which today accounts for over 90% of total production (Agriculture and Agri-food Canada, 2008). Although Canada competes with imports from the Chilean industry, its advantage in terms or quality, shelf life and geographical proximity to the USA has seen it become the dominant supplier of fresh, farmed fish to the US market (GSGislason & Associates, 2006).

The remaining eight percent of global production comes out of smaller industries that are located throughout the world including Australia and New Zealand (NZ) in the southern hemisphere, and the Faroe Islands, Iceland, Turkey, Ireland, and Japan in the north. Majority of these industries developed in the 1970-90s, and tend to produce primarily for their domestic markets. The NZ and Australian industries have grown significantly in the past few decades, with the Australian industry based on Atlantic salmon for primarily domestic consumption and NZ on Chinook species (king salmon), of which around 50 percent is exported to predominantly Japanese markets (NZSFA, 2007).

2.4 The Australian Salmon Industry

Australia's history with salmon goes back to the mid-1800s when an unsuccessful attempt was made to transfer Atlantic salmon and brown trout eggs imported from England to the rivers of New South Wales and Tasmania for recreational purposes (Tasmanian Salmon, 2007). In the 1860s brown trout were successfully introduced into Tasmanian inland waters, forming the basis of the recreational trout fishing industry that remains active today (DPIWE, 2003). In the late 1980s, the Tasmanian government began to seriously investigate the possibility of introducing sea cage culture for Atlantic salmon that had proven to be successful overseas.

Situated below 42^{o} latitude, the southeast coast of Tasmania offered an ideal setting for salmon farming as it provided cool, temperate and sheltered waters within the thermal tolerance needed for salmon. Due to a total ban on the import of all salmonid products into Australia that was enforced under the *Animal Health Act* in 1975 (DPIWE, 2003), the genetic material to start the industry was sourced from a hatchery in Gaden, located along the Thredbo River in NSW (PIRSA, 2003). This strain of Atlantic salmon was originally sourced from the River Phillip in Nova Scotia, on the east coast of Canada in the mid 1960s (Elliot and Innes, 2003). After a series of quarantine checks, the ova were introduced into Tasmania at which time the government, together with industry partners established the first hatchery in the town of Wayatinah in the Central Highlands. In 1986 the surviving fish were transferred to the first sea farms in the Huon River estuary near the town of Dover in south-eastern Tasmania (Tassal, 2011). This stock was the basis of the first commercial quantity of 53 tonnes ready for sale in 1987 (Heen et al., 1993).

Today, Tasmania accounts for the majority (95%) of salmonid production in Australia, with the remainder occurring in NSW (143 tonnes) and Victoria (850 tonnes), both of which predominantly use salmonids to stock selective waters for recreational purposes (DPI Vic, 2011). The ongoing growth in the industry has seen it become the largest aquaculture industry in Australia, accounting for 37 percent of total aquacultural production in 2008-09 (ABARE & BRS, 2010). During this period it produced 29,700 tonnes, making it the second largest seafood industry in Australia by volume (13% of total), only slightly under the sardine fishery at 31,500 tonnes (13%). In terms of value, for the same year it generated AUD$323 million (15% of total), second to rock lobster at AUD$404 million (18%). The strongest growth in the industry occurred between 2002–03 and 2006–07, driven by the combination of domestic marketing campaigns and extensive R&D funded by the industry (DPIW, 2009). The bulk of production concentrated in the south-east corner of the state, with a smaller amount of production taking place in Macquarie Harbour on the west coast, and a very small amount coming out of the Tamar Valley in the north. The industry is currently in an expansionary phase, with the three largest producers receiving government approval for additional licences in Macquarie Harbour in 2012. This will enable the industry to achieve its ambitious plans to increase production by an additional 14,000 tonnes per annum (DEDTA, 2011).

Unlike the larger producing nations who trade a significant amount of their produce on the global market, the majority of Tasmanian production (93%) is consumed within Australia, with small volumes sent predominantly to Asia (DPIW, 2009). The fresh salmon sold has minimal competition in the marketplace because the importation of uncooked salmon from other countries is prohibited under *The Quarantine Act 1975* so as to protect the industry from any potential biosecurity risks. However, this is not the case for smoked product, which competes with cheaper imports from Europe.

Whilst the Tasmanian industry has benefited from adopting many of the technologies and agribusiness models developed by the more established industries in the northern hemisphere (Otton & Dooley, 2010) it has had to develop its own strategies to address a number of issues that are unique to the Tasmanian context. The first relates to the early maturation of fish that is a major source of lost productivity for the Tasmanian industry. The early onset of sexual maturation is undesirable as this causes fish to divert their energy into gonad production, resulting in significant degradation of flesh quality and a subsequent loss in market value (CSIRO, 2006). This is a problem for the Tasmanian industry for two reasons. Firstly, the original genetic stock from Canada is derived from a strain of Atlantic salmon that unlike those used in other industries, sexually matures after just one winter at sea. This genetic disadvantage is further emphasized by the water temperatures in Tasmania, which are higher (8-18^{o}C) and less variable than other areas in which salmon are grown. Although this has given Tasmanian producers an advantage over northern hemisphere industries in terms of being able to harvest fish all year round (Heaney et al., 1999), it has had the undesirable affect of increasing the speed at which fish sexually mature (Porter et al., 2002).

Due to the restriction on the importation of new genetic material under the *Animal Health Act 1995*, the industry has been unable to utilize genetic material from other industries to overcome the early maturation problem. This option was explored in the early 2000s, as a solution to the significant decline in productivity the industry was experiencing at this time. However it was decided that this was not a good option as it posed a significant biosecurity risk and had the potential to jeopardise the desirable flesh characteristics and tolerance to the higher water temperatures of the existing Australian stock (Elliot, 2003). Despite ongoing calls from the industry for the government to reconsider this ban it continues to be a major limitation for productivity growth. In response, the industry has adopted a number of management strategies that involve the manipulation of genetic and environmental factors to minimize the impacts of early maturation on productivity.

The first is photoperiod manipulation, a strategy that is used widely throughout the salmon industry across the world to stagger production throughout the year (FAO, 2011b). This involves the use of artificial lighting to mimic the day length changes that trigger the onset of smoltification and sexual maturation in the wild. The normal physiological onset of smoltification occurs in late spring, which is October-November in the southern hemisphere. In the Tasmanian industry, some of the smolts are left to undergo this process naturally, and are therefore referred to as 'spring smolts'. In order to meet year round demand, two types of out of season smolts are produced through the manipulation of lighting. The first are referred to as 'out-of-season' smolts. These are produced by bringing forward both winter and spring lighting patterns, forcing the fish to undergo smoltification as early as April. The second category, known as 'marine pre-smolt' have only the spring pattern advanced, which brings forward the process a couple of months to around July. This is done in the hatchery with the use of lighting and curtains (Figure 8). This process is also used at the marine stage to trick the fish into thinking that it is not the correct season to spawn. The addition of light during the dark phase, just prior to the winter solstice causes a delay in maturation and a subsequent push back of harvest time by as much as eight weeks (Woolcott et al., 2003).

Figure 8: Lighting and curtains used at hatchery for photoperiod manipulation

The second strategy involves the manipulation of the fish's sex-determination system, the biological system that determines the development of sexual characteristics. The purpose of this is to produce all female stock, as males have been found to sexually mature at a faster rate than females (Taranger et al., 2010). Sex-determination in salmon is genetic, with males and females having different gene sequences that determine their sexual morphology. Similar to humans, they have what is referred to as an XX/XY sex-determination system in which the female fish have two copies of the X chromosome (XX), and the males have one X and one Y (XY). The process used by salmon farmers to produce all females begins with the production of both male and female eggs using the procedure described earlier in the chapter. At the first feed, a small amount of testosterone is added which causes the female eggs to form male gonads, however their genetic sequence remains unchanged (XX). These false male fish (XX) are then used as the broodstock that are bred with females (XX) resulting in the formation of only females as there is no Y sequence available.

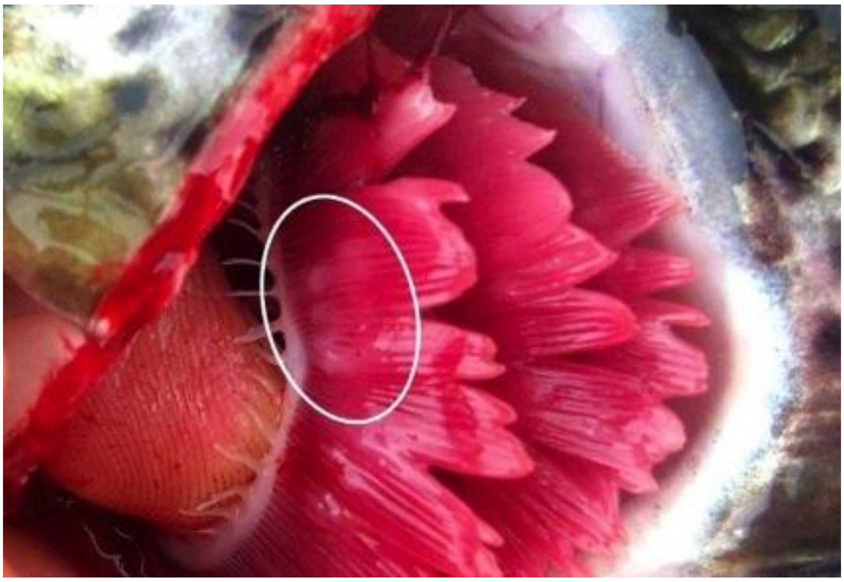
The final strategy is the production of sterilized fish so as to avoid the onset of sexual maturation altogether. There are a number of methods available to do this, with the Tasmanian industry adopting one that involves exposing the eggs to a pressure shock at a key stage in the fertilization process (Jobling, 2010b). This shock is applied using a specially designed machine, with the timing of the process critical to its success. The pressure shock is applied just as the parent cells are splitting, which results in the formation of three chromosones (XXX) instead of two (XX) when the DNA split. These fish, known as triploids, do not sexually mature as this DNA manipulation blocks cell meiosis, the process by which cells divide in sexually reproducing organisms to create gametes (Piferrer et al., 1994). This process has no impact on the flesh quality or safety of the fish for human consumption, however the fish tend to be more susceptible to environmental stress and prone to deformities to their jaws and gills (Taranger et al., 2010). These fish are currently grown only at the Macquarie Harbour site on the west coast of Tasmania, and are used to fill the gap in the market between the end of harvest for a certain year class in February, and the commencing of the next harvest in May.

Another complication associated with the warmer water temperatures is the rate at which fouling species such as algae, sponges and sea squirts grow on the nets used for the sea cages. This can have detrimental effects on fish health as the growth of these marine organisms blocks the flow of clean, oxygenated water into and out of the sea cage, and provides reservoirs for disease-causing organisms (Macleod and Eriksen, 2009). In recognition of the considerable cost to continually remove, clean and replace the nets, the industry applied for a permit under the Australian Pesticides and Veterinary Medicines Authority (AVPMA) to conduct research on the use of unregistered antifoulant paints. The main ingredient in these paints is copper, with a smaller quantity of zinc. Both of these are naturally occurring trace metals, that when found in concentrations exceeding normal requirements, can be toxic to a range of organisms. Therefore the permits issued under the APVMA place restrictions on the location and methods that could be used to apply the paints, and require that research be conducted to assess the potential impact of these substances on the surrounding marine environment. This research continues to be undertaken on behalf of the industry by a research team at the University of Tasmania's (UTAS) Tasmanian Aquaculture and Fisheries Institute (TAFI), and a separate program run by the Department of Primary Industries, Water and the Environment (DPIWE), both of which involved the monitoring of a range of environmental indicators at the marine sites that were trialing the paints. The results from five years worth of data collected by the TAFI group indicated that some of the sites had elevated levels of copper and zinc in comparison to control sites that were also monitored (Macleod and Eriksen, 2009). In addition to the direct impacts on the marine environment, the process of cleaning the nets results in a sludge that contains a high level of the metals, making the subsequent treatment and disposal of the sludge a difficult and costly process (D. O'Brien, pers.comm, May, 2011).

Since this time, the industry has made a concerted effort to find solutions to the fouling problem that does not involve copper based paints. This includes the use of nets that are made of materials that fouling is unable to grow on, and the development of the Marine Inspector and Cleaner (MIC), a hydraulically powered device that allows for in-situ cleaning of the nets. This was recently developed by MIC Pty Ltd, a local company that was formed as a joint venture between Seafarm Systems, a Tasmanian based aquaculture equipment supplier, and Tassal, the largest salmon producer in the Tasmanian industry. The major benefit of this is that it allows the nets to be cleaned on a regular basis, resulting in minimal growth and a reduced need to use the anti-fouling paints. However, studies undertaken as part of the above-mentioned TAFI project found that this process actually increased the levels of copper and zinc that are found in the surrounding benthos due to the fact that once removed by the vacuum, the growth from the nets is deposited directly into the marine environment (Macleod and Eriksen, 2009).

A further distinction of the Tasmanian industry is the widespread loss of life caused by Amoebic Gill Disease (AGD), which is endemic to the waters of southern Tasmania (Adams et al., 2002). The gill amoeba (*Neoparamoeba pemaquidensis)* is a microscopic, single celled organism that attaches to the gills (Figure 9), clogging them and preventing the flow of oxygen (CSIRO, 2006). This can have a serious affect on the health and growth rate of the salmon, and if left untreated can result in stock losses of up to 80-90 percent over the summer months when the disease is more prevalent (O'Sullivan, 2011). Whilst AGD has also been found to affect salmonids in France and New Zealand (Powell and Clarke, 2002), the impacts are not as detrimental as in Tasmania, where the disease is considered to be the most serious health problems faced by the industry (Dykova et al., 2000).

Figure 9: Characteristic white patches on the gills of salmon caused by AGD



Source: TSIC, 2011

The industry has responded to this challenge by adopting a management technique known as freshwater bathing. This involves the transportation of freshwater from dams located in close proximity to the marine operations via a barge where it is placed in a pen lined with a large tarpaulin (Figure 10). The fish are then pumped from their existing pen to one containing the freshwater where they bathe for up to four hours. Since the amoeba is a saltwater species, exposure to the freshwater causes them to die and fall from the gills of the fish into the water which is discarded into the marine environment once the process has taken place (Powell and Clarke, 2002). Bathing is undertaken every 30-100 days depending on the time of year, with as many as eight taking place in the 18 months that the fish spend at sea (O'Sullivan, 2011). This process is costly in terms of labour and equipment (Elliot and Kube, 2009), costing producers in excess of $25 million for 2006/07. In addition to the economic costs, the process requires a large amount of freshwater, which during times of drought can be costly in terms of the impacts on the lower sections of the natural watercourses from which the water is diverted.

Figure 10: ***Infrastructure required for freshwater bathing operations***

a. pump

b. tarpaulin lining used for bath

Addressing the problem of AGD continues to be a priority for R&D in the industry as a means to reduce the associated environmental and economic costs. Previous research has trialed the use of alternative treatments such as the use of Chloramine T and various vaccines (Adams and Nowak, 2003), and more recently using hydrogen peroxide which is used for the treatment of parasites in other fisheries, with preliminary lab trials yielding promising results for the treatment of AGD (Nowak et al., 2010). Selective breeding for resistance to AGD is being explored by the individual producers, and on behalf of the industry through the selective breeding program being jointly run by CSIRO and Saltas, discussed in more detail below.

Three of the producers have recently received government approval to expand production on the west coast of Tasmania, where they are able to take advantage of the growing conditions that eliminate two of the above-mentioned issues. Firstly, there is currently no sign of AGD in this region, and the likelihood of it becoming a problem is low due to the high volume of freshwater that fills the top 3 meters of the water column (K.Ellard, pers.comm, August, 2011). Secondly, the waters in this area are naturally very dark and murky, which limits the amount of sunlight that is able to penetrate the water, and in doing so, prevents the troublesome biofouling of nets that occurs on the east coast (M.Jones, pers.comm, August, 2011). A minor difficulty for this development is the availability of operational staff, as there is not a large population on the west coast to draw on.

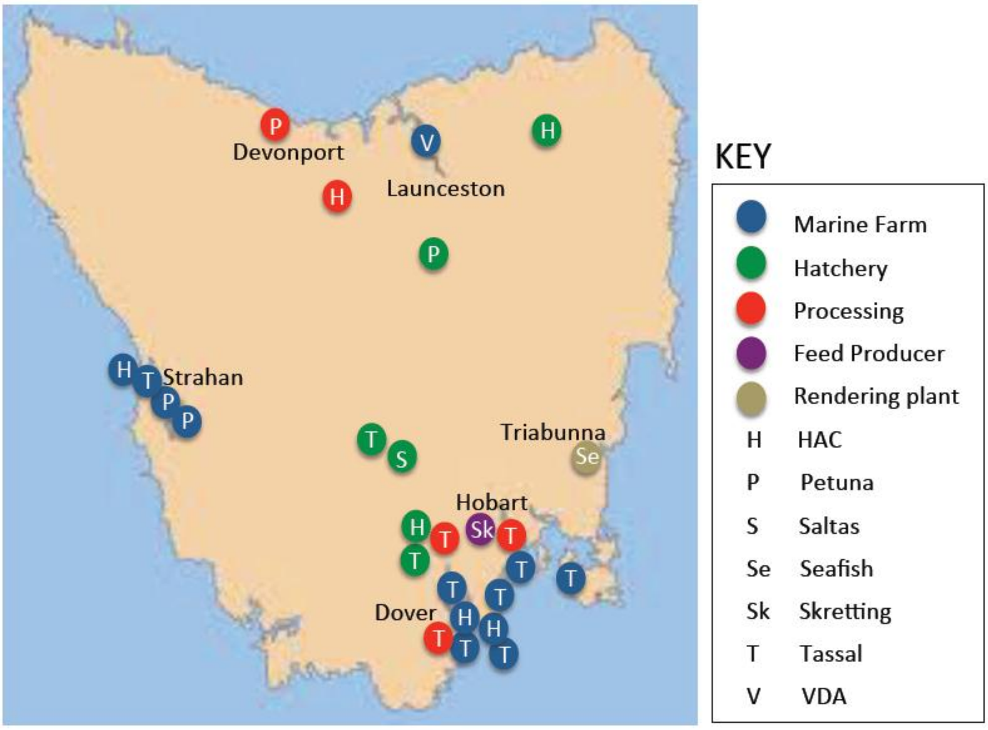
2.5 Stakeholders in the Tasmanian Salmon Industry

The Tasmanian salmon industry is made up of a number of upstream and downstream stakeholders. A brief summary of these is provided to give an overview of the industry.

2.5.1 Salmon Producers and Processors

Of the eleven companies that commenced salmon aquaculture in Tasmania during the 1980s, three remain, which together with a newcomer make up the industry today. The largest producer is Tassal who in 2010 were responsible for over 70 percent (12,000t) of total production (Tassal, 2011). The company was originally established by the Norwegian company Noraqua, who were invited by the Tasmanian Government to set up salmon farming in Tasmania in the early 1980s (Nortas, 2000). By 1986 the company had changed its name to Tassal. It was the first to trial sea cage operations located in the pristine waters near Dover (Figure 11).

Figure 11: Location of businesses from the Tasmanian salmon industry



Not to scale

In 2003 it became a public company listed on the Australian Stock Exchange (ASX), grew to become a vertically integrated company. This was achieved through a combination of organic growth, as well as through the acquisition of Nortas, a former competitor in 2003, and a merger with Aquatas in 2005 (Tassal, 2011). Tassal's freshwater operations are comprised of an older style flow-through hatchery (1.3 million fish capacity) located in Russell Falls and a new state-of-the-art Recirculation Aquaculture System (RAS) that is in the Huon Valley. With a capacity to hold 4 million smolts, this facility is the largest of its kind in the world (McGowan, 2010). The AUD$25m facility has been operational since 2010, and is intended to allow Tassal to double production by 2015 (Asman, 2010) whilst simultaneously reduce their water consumption as a volume is able to be recycled. This system has the added benefit of allowing for the sludge that contains the uneaten feeds and faecal matter to be collected and sold as a fertiliser to a local agricultural enterprise.

Tassal currently holds seven marine licences, six of which are located on the east coast, with one on the west coast in Macquarie Harbour. The recently approved application to expand production on the west coast will see Tassal with an additional two marine licences. Its processing facilities include a wet processing site where all fish from the south coast marine sites are gutted using a fully automated, mechanized system, and two value-adding facilities in Margate and Huonville. A recent AUD$15m upgrade to the Huonville plant in 2009/10 has allowed Tassal to double production capacity from 14 head-on and gutted (HOG) tonnes to 28. The company has also extended its operations to include two retail outlets, one in Hobart and the other in Melbourne. In total the company now employs over 700 people. In addition to the financial benefits that have come about from the increasing economies of scale, the company has also benefited from the expansion of its distribution channels to include the major supermarkets (Venture Positioning Services, 2008) to whom it sells a range of fresh and value-added products. Tassal has ambitious plans to further expand by increasing exports to Asian markets.

Huon Aquaculture (HAC) is the second largest producer, responsible for approximately 10,000 tonnes of Atlantic salmon and 1,000 tonnes of ocean trout (*Oncorhynchus mykiss*) in 2010 (O'Sullivan, 2011). The company was established in 1985 by a local farming family, and since this time has continued to grow to become a vertically integrated company through a combination of organic growth and acquisitions. The company was the first in the Tasmanian industry to install a RAS hatchery in 2006, and it supplies 40 percent of smolts to their marine farms (HAC, 2011a). HAC also operate three smaller hatcheries, including Australia's oldest hatchery located in Springfield, which they purchased in 2009. This hatchery is geared towards the production of eggs for the export market, and currently exports to over 10 countries and provided some of the stocks required to rebuild the Chilean industry in 2009.

HAC currently hold two marine licences, one located in the Huon Estuary and D'Entrecasteaux Chanel on the east coast, and the other in Macquarie Harbour on the west coast which together cover a total of 600ha. It is also part of the group planning to expand production on the west coast, which will see them with an additional two marine licences. In 2010 it converted an old baby food factory located in the north-east of the state near Devonport to a combined wet and value-adding processing facility. This is strategically placed to allow the firm to process fish from both the east and west coast marine sites (Figure 11). In 2006 it acquired a value-adding facility located in Adelaide from Springs Smoked, which it uses to produce a range of goods including pate, smoked salmon, gravlax and caviar. In total, the company employs over 130 Tasmanians and an additional 120 South Australians. HAC has contributed to the development of a range of technologies for which it has won awards for environmental best practice. These include the *Aquasmart* feed system that matches feed supply to fish appetite. Another initiative is the specialized fish runs that minimise stress to fish during the handling and harvesting processes.

The third Tasmanian company Petuna, produces and processes a range of seafood from both aquaculture and wild capture fisheries. It was established in 1950 as a family business focused on wild capture species, and has evolved overtime to become Tasmania's largest multi-species seafood company. Its wild capture operations are concentrated in the Southern Ocean and include Hoki, Pink Ling, Blue Eye Trevalla and Warehou. It moved into aquaculture in the early 1990s with the acquisition of West Coast Salmon, expanding further in early 2000s with the purchase of the original Salmonid producer on the west coast, Sivrep. Similarly to the above-mentioned companies, it is vertically integrated with a hatchery located in Cressy in the central north of the state, sea-cage operations based in Macquarie Harbour and a processing plant in Devonport (Figure 11). It is the third company involved in the Macquarie Harbour expansion, which will see Petuna with an additional licence.

The species cultivated by Petuna are predominantly Atlantic salmon, as well as a smaller amount of Ocean Trout. The produce is predominantly sold to the domestic market, in particular through Woolworths chains, and Petuna's trout is well recognised as the key ingredient for the signature dish of world-renowned chef, Tetsuya. Its plant at Devonport processes all produce from its own marine sites as well as those from Van Diemen Aquaculture that are grown under contract for Petuna. In addition to this, they also process all fish from Tassals west coast operations due to biosecurity rules that prevent them transporting this produce from the west coast to their own processing facilities located on the east coast. This facility is currently undergoing significant extensions to accommodate the expected increase in production associated with the industry expansion in Macquarie Harbour. The company forms part of a growing number of seafood operations across the world recently acquired by Sealord, New Zealand's largest seafood producer who now own a 50 percent share in Petuna.

The fourth company is Van Diemen Aquaculture (VDA), which is a smaller company, and the sole operator in the Tamar Valley located approximately kilometres 45 kilometres north-west of Launceston (Figure 11). The company was established in the early 2000s by a group of ex-wild capture fishermen who attempted to farm Ocean Trout in the Tamar River. Although this was not successful, they later found Atlantic salmon to be a more suitable species, and today the company grows salmon at the marine stage under contract to Petuna. The original hatchery in Wayatinah, and the nearby Florentine hatchery (Figure 11) are owned and operated by Saltas. They form a co-operative that is overseen by a board comprised of government and industry representatives. The Tasmanian State Government holds a 25 percent voting right, with the remainder shared between Tassal, HAC and Petuna. The hatcheries produce both fertilised eggs and smolts that are sold at the cost-of-production to the various industry partners, with Tassal accounting for majority (80%) of purchases. It is also heavily involved in R&D, most notably the selective breeding program that has been running since 2004 in partnership with CSIRO. In addition to these large companies, there are two privately owned hatcheries by the name of Snowy Range and Mountain Stream that supply smolts and eggs to the various producers as required. Otherwise there is not much more to the production side of the industry. In terms of value-adding there are a small number of boutique smoke houses such as the Bruny Island Smokehouse that service niche markets.

The expansion of the industry has meant that producers have been able to capitalize on the increasing economies of scale, which has to some extent been passed onto the Australian public in the way of reduced retail costs of salmon. This has been further emphasized by the increasing sales through the major retailers, Coles and Woolworths who have used their market power to drive down the price, which to some extent is passed on to consumers, making this nutritious food more affordable and accessible to the wider Australian population.

2.5.2 By-product Processing

After slaughter has taken place, the fish are sent to wet processing facilities to remove the viscera to make HOG. Majority of this is sent directly to market with the remainder sent for further processing to create value-added products such as fresh fillets and smoked products. As a result of both these processes a range of 'by-products' are generated including the frames and viscera from the initial processing as well as heads, skins and trimmings from the value-adding stage. A small portion of the heads and frames from HAC are sent to a Mars owned pet food manufacturer in Victoria, with some from Petuna sent further afield to France to be used for pet food. Until recently, the viscera as well as the mortalities from the hatcheries and salmon farms were sent to landfill, however since 2009 these materials from the east coast operations owned by HAC and Tassal have been sent to a nearby Tasmanian rendering plant to be processed.

This plant is owned and operated by Seafish, a local company established in 2000 as a commercial fishery that operated in the waters of the Southern Ocean surrounding Tasmania. Their key operation was the capture of small pelagic fish including redbait, jack mackerel and blue mackerel that were primarily sold as baitfish. The company was set up as a vertically integrated entity comprised of fishing vessels, a wharf and processing facility located in the small town of Triabunna, 75 km north of Hobart (Figure 11). The processing facility includes a freezer plant to prepare and store the baitfish prior to market, as well as a fish rendering plant for producing fishmeal and oil. In 2006 there was a marked decline in redbait catch believed to be the result of warmer water temperatures, which led Seafish to look for opportunities to diversify its business and income. The company saw an opportunity to utilise its existing rendering plant to add value to the 'waste' generated by the growing salmon industry which included the by-products from processing (heads, frames and guts), as well as the mortalities collected from sea cages.

The company received a $10,000 grant from Enterprise Growth Program to develop a business plan that was presented to Tassal and Huon, who in February 2008, began to divert their waste to Seafish. To help fund the technical upgrades required to enable their existing plant to handle salmon waste, it secured a further $150,000 from the Department of Economic Development, Tourism and the Arts through the Tasmanian Innovations Program Grant. At the time of writing, trials are being undertaken to treat the mortalities from the west coast industry that are currently buried in land owned by Forestry Tasmania. This will be important as the industry expands with the Macquarie Harbour development as discussed above.

Since Seafish commenced the project, the plant has undergone significant changes, and in 2010 the original plant, an older style facility, that used heat to cook and extract oil and protein, was converted to one that is largely driven by enzymes. This is known as the hydrolysate process. It begins at the salmon producers' facilities with the application of acid to stabilize the waste. It is then transported to the Triabunna plant where it is gently heated to release the endogenous enzymes found in the guts of salmon. These then act on the larger protein molecules by breaking them down into their building blocks of peptides and amino acids. As this occurs, the mixture liquefies, and the oils contained within the waste are released. The oil is then separated, and the remaining mixture, referred to as crude hydrolyzate is subject to evaporation to remove some of the water. This process has the dual benefits of requiring less energy to drive the system, as well as the improved nutritional value of the resulting mixture as the lower temperatures do less damage to the proteins. At the time of writing, Seafish are also experimenting with a range of exogenous enzymes in order to extract a higher quality final product that could potentially be used for human grade fish oil supplements.

2.5.3 Feed Companies

The bulk of aquafeeds used by the Tasmanian salmon industry come from two Australian-based suppliers, with a smaller quantity imported from Danish companies

BioMar and Ala Aqua. The first of the major suppliers is Skretting, an international company owned by the Dutch group, Nutreco who produce a range of animal feeds for markets across the globe. Skretting is the world's largest producer of aquafeeds producing feeds for over 50 species of farmed fish, amounting to a total of over 1.3 million tonnes of feed per annum (Skretting, n.d). In regards to salmon feeds, it is the largest of three companies that collectively account for 90 percent of global production, of which Skretting are responsible for 36 percent (Nutreco, 2010.) Its operations are strategically located in the major aquaculture hubs throughout Asia, Europe, the Americas and Australasia. Its Australian plant is based in Cambridge, on the outskirts of Hobart (Figure 11). Here it produces a range of aquafeeds of the Australian and New Zealand markets, including feeds for barramundi, kingfish and a range of Salmonid species. The plant underwent a refurbishment in 2012 that doubled its capacity to approximately 130,000 tonnes/annum in anticipation for the planned future expansion of the salmon industry. It currently employs 58 FTE staff, including both operational and managerial staff.

The second feed company Ridleys, is an Australian-owned, publically-listed company that produces a range of feeds for terrestrial animals, aquaculture and the pet food market. Their aquafeed range includes feed for a number of species including prawns, barramundi, trout and Salmonids. It owns and operates 19 mills located throughout the states of NSW, Victoria, Queensland and South Australia. The feeds used for the Tasmanian industry represent 60 percent of the feeds made at their plant located in Narangba, Queensland. A small portion of feed comes from a third company, Biomar, however unlike the feeds sourced from the above-mentioned companies, those from Biomar are not produced in Australia. Biomar was originally established in the 1960s by a group of Danish fish farmers. It was taken over by a Norwegian company in the late 1980s. It has since grown to become one of the world's largest suppliers of fish feed, supplying over 50 countries with feeds for over 25 different species. Its primary market is Europe, including the UK, with a focus on providing feeds for salmon, trout, eel, sea-bass and sea-bream.

The feeds produced by both companies are made from a variety of raw materials from terrestrial and aquatic origin. They are formulated according to a set of specific nutritional criteria that will be discussed in more detail in chapter three. A summary of the exact composition of the feeds and the source of the raw materials will then be provided in chapter five.

2.5.4 Government

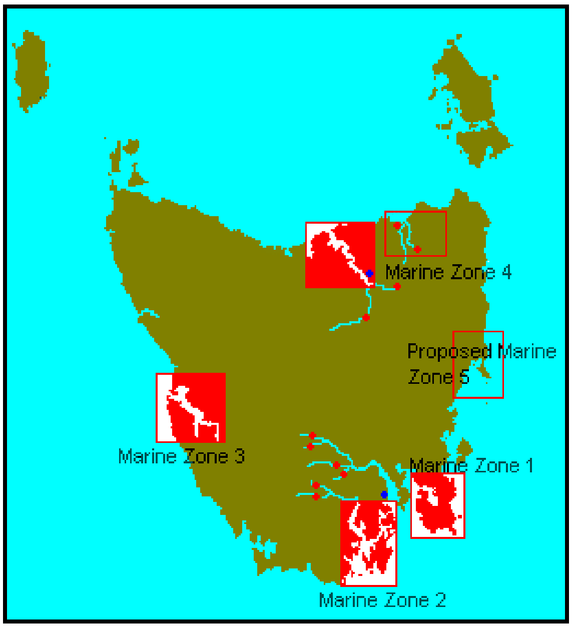
The salmon industry is supported in various ways and regulated by both state and federal governments. At the state level, all marine farming entities are regulated by the Department of Primary Industries, Parks, Water and the Environment (DPIPWE) under the *Living Marine Resources Management Act 1995,* (LMRMA) and the *Marine Farming Planning Act 1995* (MFPA). These statutes form part of an overarching industry-wide environmental management system (EMS) for aquaculture in Tasmania. All salmon producers must apply for licences under the LMRMA, and once granted, licences holders must uphold conditions that relate to such issues as the management of waste, control of chemical, monitoring of the benthic environment and visual amenity (Woods et al., 2002). The MFPA establishes mechanisms for the preparation and approval of Marine Farming Development Plans (MFDP), which must be accompanied by a comprehensive Environmental Impact Statement (EIS). Licences issued under this Act vary in regards to specific conditions based on specific environmental priorities for the marine zone in which the licence is allocated. The licences also prescribe operational requirements to which marine farmers must adhere to, and require annual reports to be submitted that monitor the health of the underlying benthos, concentration of copper and zinc in surrounding sediments, antibiotic use, wildlife interactions and fish escapes.

All freshwater fisheries, including salmon hatcheries are licenced under the *Inland Fisheries Act 1995 and the Inland Fisheries Regulations 1996*. This is administered by the Tasmanian Inland Fisheries Service (IFS). Both freshwater and marine operations involve the extraction of freshwater, which requires them to apply for water licences. These are issued by the Water Resources Division of DPIPWE, who are responsible for enforcing the provisions of the *Water Management Act 1999* (WMA), which forms part of the State's resource management and planning system. The licences detail specific conditions that accompany the allocation of water resources such as the source of the water and the conditions under which the licence holder is able to extract the water.

The Environmental Protection Authority (EPA) is another division of DPIPWE. It was established in 2008 under the *Environmental Management and Pollution Control Act 1994* (EMPCA), which also forms part of the above-mentioned resource management and planning system for the state of Tasmania. The EPA works in conjunction with local government authorities through the inclusion of environmental conditions to permits issued under the *Land Use Planning and Approvals Act 1993* (LUPA). In regards to salmon production, environmental issues of relevance to the EPA include those relating to waste water treatment, solid waste treatment and the use of antifoulant paints.

The Fish Health Unit (FHU) at DPIPWE is responsible for enforcing the Commonwealth *Quarantine Act 1908* and the Tasmanian *Animal Health Act 1995* which provide the legislative basis for the importation and movement within Tasmania of animals and defined restricted materials. Of particular importance to the Salmonid industry are the restrictions on the movement of fish (dead or alive) between four defined geographical regions that have been gazetted as "restricted areas" for the control of endemic diseases (Figure 12)(Ellard, n.d). Restrictions are currently in place for live fish movements out of Macquarie Harbour (Marine Zone 3). This is to control the spread of Marine Aeromonad Disease (*Aeromonas salmonicida acheron*) and Aquatic Birnavirus. Similar restrictions are also in place for fish movements out of the Huon/Channel area (Marine Zone 2). This is in order to control the spread of Rickettsial-like organism (RLO) and Salmon Reovirus (DPIWE, 2003). Permits must be issued by the Fish Health Unit to allow the movement of fish between the various production and processing sites. Permits detail conditions such as cleaning schedules, processing procedures and waste treatment that must be adhered to. Further to the above-mentioned legislative roles of the various DPIPWE organisations, they also provide ongoing R&D funding to the industry, with over $AUD2.7 million per annum in research grants (Pedderson, pers.comm, 2011).

***Figure 12*: Location of the Salmonid Biosecurity Regions within Tasmania**



Source: DPIWE, 2003

The federal Government provides funding to the salmon industry via the Fisheries Research and Development Corporation (FRDC) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Projects funded by FRDC include those relating to the monitoring of ecological impacts of antibiotics and antifoulants (Macleod and Eriksen, 2009), and the CSIRO Food Futures Flagship supports the selective breeding program that is a jointly run by the Saltas hatchery. The objectives of this research are to improve growth, increase resistance to AGD, reduce incidence of early maturation, and maintain carcass quality traits such as flesh colour and fat content (Elliot and Kube, 2009). CSIRO are also involved in the Broadscale Environmental Monitoring Program that focuses on the monitoring of water and sediment quality and benthic community health in the areas close to the marine farms to determine the impact of salmon farming on the local environment.

2.5.5 Non-Government Organisations

The industry is represented by the Tasmanian Salmonid Growers Association (TSGA), which was established in the mid 1990s by its grower members. Its tasks are to deal with Federal and State Governments and to support ongoing R&D. The body operates as a not-for-profit organization that is funded by a levy that is payable on the feeds purchased from Skretting, Ridleys and Biomar. The funds raised are used to fund industry-based research such as the ongoing Fish Health Surveillance Program, Broadscale Environmental Monitoring Program and the EU Residue Monitoring Program. The latter focuses on the access of Australian aquaculture to European markets (pers. comm, Dr. Adam Main).

The industry is also represented by the Tasmanian Seafood Industry Council (TSIC), a not-for-profit organisation that promotes aquaculture, processing and wild capture fishing entities within Tasmania. This is funded through the payment of a levy to all those who hold a licence for commercial fishing. As well as the broad projects undertaken by TSIC on behalf of the seafood industry as a whole, it also supports industry specific work such as the development of the *Environmental Management System Framework (EMS): Tasmanian Salmonid Industry* that was undertaken in collaboration with FRDC, TSGA, Phycotec and the Tasmanian State Government in 2004.

2.5.6 Tasmanian Community

Tasmania's economy has struggled to keep up with other Australian states, with historic growth patterns characterized by poor economic performance, limited employment opportunities and a lack of economies of scale (BITRE, 2008). According to the Tasmanian Treasury (2011), the number of Tasmanian job seekers receiving income support was equal to four percent of Tasmania's labour force in 2010, compared to 2.6 percent nationally. Despite the need to generate jobs, there is a strong anti-growth movement in the community that has led to the opposition of a number of proposed industrial developments, from the iconic backlash to the construction of the Franklin dam in the early 1980s, and more recently, the conflict over the proposed wood pulp mill in the Tamar Valley. Tasmania has had a powerful Green political party for many decades, with the Greens twice entering into a formal coalition with the Labour Party to form government.

Employment in agriculture, fisheries and forestry accounts for 5.7 percent of the Tasmanian workforce, which is almost double the national average (3.2%)(DEEWR, 2011). However this sector has recently suffered significant losses that have largely been the result of changes to the structure of the forestry industry. Over the past five years it has experienced a 50 percent decline in employment from 7,000 in 2006 to 3,500 in 2011, which is the equivalent of 1.5 percent of the state's total employment (Schirmer et al., 2011). These losses are due to a general decline in forestry activity, combined with the recent closures of woodchip and pulp mills. This situation is expected to worsen with the implementation of the joint State and Commonwealth Government *Tasmanian Forest Agreement* that will see 430,000 hectares of high conservation native forest placed in immediate informal reserve by the state (Giddings et al., 2011). As part of the $276 million package, $85 million has been earmarked for employee assistance, retraining, and exit packages for forest workers and contractors. However if this is to be successful, it will need to be accompanied by the creation of job opportunities in other industries that require similar skill sets.

The salmon industry plays an increasingly important role in Tasmania's economy. In 2010 it contributed $152 million dollars (0.5%) towards Gross State Product (GSP), provided direct employment opportunities equivalent to 1,100 FTEs (DEDTA, 2011), as well as an additional 3,850 jobs indirectly through supporting industries such as transportation (TSGA, 2010). Any future expansion in the industry could create much needed employment opportunities throughout a number of the regions of the state that have experienced significant employment losses over the previous decade as a result of the decline in forestry.

2.6 Measuring Efficiency in the Tasmanian Salmon Industry

As can be seen from the above discussion, the Tasmanian salmon industry is an important source of employment and revenue for the local economy as well as a good source of nutrients for the Australian population. Whilst there is significant work being done to ensure that the ongoing growth of this industry is occurring with minimal impact on the environment, if this is not able to be measured there is no way of assessing the achievements made, or to identify areas for further improvement. This is vital if they are to keep abreast of the issues identified in chapter one. For this reason a comprehensive assessment of efficiency that covers matters pertaining not only to economics, but also environmental factors needs to be undertaken. The following chapter will provide an overview of the measures that are traditionally used to assess the efficiency of salmon aquaculture and identify where improvements are needed. Following this, chapter four will discuss existing tools that can be used to fill the gaps identified.

Chapter 3: The Status Quo in Productive Efficiency of Salmon

As discussed in chapter one, the productivity gains made by the food industry over the past half a century has been achieved through ongoing efforts to improve the economic efficiency of production. Interestingly, two of the metrics commonly used to measure the ratio of input to output in salmon aquaculture also deliver an insight into environmental objectives. These are the feed conversion ratio (FCR) and the numerous variations of the fish-in:fish-out (FIFO) ratio. It is no coincidence that both of these relate specifically to feeds, as these are considered to be the key driver of productivity growth and cost savings within the sector (Asche and Bjorndal, 2011). This chapter will examine these two measures, the drivers that have led to improvements in these over time and the economic, environmental and nutritional outcomes that have been achieved as a result. Following this an assessment will be made as to the suitability of these metrics to assist in achieving the efficiency gains that will be required to meet future challenges facing the food system.

3.1 Feed Conversion Ratio

As mentioned in chapter two, salmon are considered to be one of the most efficient and successful species under intensive production (Forster, 2002: Gatlin, 2002). The basis of this assessment relates to the ability of salmon to convert nutrients and energy from their diets into body mass. This form of efficiency is most commonly measured using the feed conversion ratio (FCR), also known as feed conversion efficiency (FCE), which compares the quantity of feed required to produce a certain quantity of fish. There are two different ways to measure FCR. The first of these is known as biological FCR (bFCR), which is used to measure the net quantity of feed required to produce one kilogram of fish. This is considered to be the ‘true’ or theoretical FCR based on the metabolic requirements of the fish, however it fails to take into consideration the losses that occur in practice through uneaten feeds and mortalities. To account for these losses, economic FCR (eFCR) is used to measure the amount of feed purchased per biomass produced (Equation 1). Regardless of which of these measures is used, the lower the FCR the better as this indicates that less feed is required to produce the same output. Since the latter of these provides a more comprehensive assessment of efficiency, unless otherwise specified, any mention of FCR for the remainder of this research will refer to eFCR.

$$eFCR = \frac{Mass\ of\ feed\ (dry\ weight)}{Mass\ of\ fish\ harvested\ (live\ weight)}$$

Equation 1

Obtaining a low FCR has been, and continues to be a major focus of research and development within the aquaculture sector as well as other livestock industries, primarily as a means to improve the economic efficiency of production. The reason for this is clear when you consider that feeds comprise a significant portion of the total variable costs for majority of intensively farmed animals, therefore significant savings can be achieved through small reductions in the amount of feed required to produce a set output. This is certainly the case with salmon production where feeds account for between 60 to 70% of the total variable costs (Tacon, 2005). As a result of this continued focus on feed efficiency, global salmon production has seen a decrease in FCR from around 3:1 in the 1980s (Asche and Bjorndal, 2011) to the current average of approximately 1.3:1 (Tacon and Metian, 2008).

Care must be taken when interpreting these values as the results can be misleading due to the different units used for the denominator and numerator of the above equation. For the feed, dry weight is used which does not take into account for the water content of the raw materials before they are processed into feeds. This is in contrast to the live weight measure used to represent the aquaculture species that does take water into account. As such, this measure is actually an underestimate of the quantity of raw materials used to produce the fish. Even more care should be taken when comparing the results between species since the nutritional composition of the diets varies significantly. Therefore FCR for species such as salmon that use feeds that are high in protein and energy will have a lower FCR than for species such as cattle whose diets contain high amounts of indigestible roughage.

3.2 Measures of Forage Fish Dependency

The measures of efficiency that will be discussed in this section stem from what has long been considered to be the most significant issue facing the future of aquaculture – the availability of fishmeal (FM) and fish oil (FO) used in aquafeeds, and the ecological status of the wild-capture fisheries from which the majority of these are derived (Naylor et al., 2000; Naylor et al., 2009: Nordahl, 2011; Tacon & Metian, 2008). Before describing these measures, a brief overview of the FM and FO industry will be provided so as to highlight the importance of these materials in the historic and future development of the salmon industry.

3.2.1 The Fishmeal Trap

Recall from chapter two that the diets of salmon in the wild vary depending on the availability of suitable organisms upon which to feed (Jobling, 2010a). An important trend to note is that as the fish matures the consumption of small, oily fish that live in the pelagic (surface) zone of the ocean play an increasingly important role in their diet. Based on this crude understanding of salmon nutrition, pelagic species such as sardines were added to the wet feeds that were used in the early days of salmon aquaculture (Tacon, 2005). As the industry moved towards a more streamlined approach through the use of commercialised pellets in the 1980s, these pelagic fish were rendered into FM and FO that were the main source of protein and oils in the formulated feeds. These materials are sourced from wild-capture fisheries commonly referred to as reduction, industrial or forage fisheries.

Reduction fisheries and the associated processing industry that converts the fish into fishmeal and fish oil products (FMFOP) had been in existence well before the blue revolution took hold. Production of these materials began in the early 19th century in

Europe and North America as a way to turn surplus herring catch into valuable oils (Ariyawansa, 2000). These were used for a range industrial purposes such as tanning and soap production, whilst the FM was seen as a less valuable by-product used in fertilisers and animal feed (FAO, 1986). Production of FMFOP shifted to the southern hemisphere in the late 1950's as Peruvian entrepreneurs took advantage of the gap in the market that was created by the collapse of the Californian sardine industry (Laws, n.d). This allowed them to acquire cheap boats and rendering machinery that allowed them to take advantage of some of the world's most fertile waters that surrounded their coastline. The combination of these factors saw output of FM grow very quickly from 350,000 tonnes in 1960 to 1.2 million tonnes in 1962 (IFFO, 2009a). This additional supply soon found a market, becoming a popular source of protein and energy for the growing poultry and pig industries, which respectively accounted for 50% and 48.2 percent of total FM production in the 1960s (Jackson, 2011). At this time FO was considered to be the less valuable by-product and was mainly burnt for fuel along with a wide variety of other industrial applications (Shepherd et al., 2007).

This all changed with the onset of the blue revolution in the 1970s, which saw a shift in the consumption of FMFOP from agriculture to aquaculture. Today aquaculture accounts for 60 percent of FM and 81 percent of FO that is produced globally, which has significantly displaced consumption from the poultry sector, and to a lesser extent pigs (Jackson, 2011). One of the key reasons that the aquaculture sector dominates the market is because these marine oils and proteins are essential to the health of the species being produced and cannot be found in other feedstocks. This is not the case for pigs and poultry for which a range of plant based substitutes are readily available (Nordahl, 2011). Nor is it the case for herbivorous freshwater fish such as carp and tilapia that currently account for over 50 percent of total aquacultural production by volume (FAO, 2012b), nor the filter feeding molluscs that make up a further 25 percent. In fact, it is not so much the aquaculture sector that dominates the FM and FO market, but rather a select few species of which salmon is one. Despite the fact that this sector accounts for only seven percent of total global aquaculture production (FAO, 2012b), it utilizes 26 percent of all the FM and 68 percent of the FO used in aqufeeds (Jackson, 2011). This is in contrast to carp that account for 37 percent of total production (FAO, 2012b) and use just 12 percent of FM and no FO (Tacon and Metian, 2008). The reasons for this will be explained in more detail in section 3.3.1 of this chapter.

This heavy reliance of the salmon industry as well as species such as shrimp and other marine finfish on FMFOP has led to widespread criticism of the expansion of these industries on both ecological and social grounds (Bostock et al., 2010). The primary ecological concern relates to the status of the reduction fisheries (Alder et al., 2008), and the impacts that this has on predatory species within the same food web (Naylor et al., 2009). This is an issue that applies to all wild-capture fisheries and as such there are a number of ways to assess the ecological status of these. One of the most long-standing and widely referred to is the assessment undertaken by the FAOs Fisheries and Aquaculture Department. The major species currently used for reduction purposes are the anchoveta (*Engraulis ringens*) (7.4Mt) and mackerel (*Scomber japonicas)* (1.3Mt) from the southern hemisphere as well as Atlantic herring (*Clupea harengus*)(2.5Mt), blue whiting (*Micromesistius poutassou*) (1.3Mt) and Japanese anchovy (*Engraulis japonicus*) (1.3Mt) from the north (Shephard et al., 2005). According to the latest FAO assessment, all of the above-mentioned pelagic species are classified as being *fully exploited* (FAO, 2012b). Despite the somewhat grim situation that is suggested on account of the use of the word *exploited*, according to the FAO a fishery that is fully exploited refers to one where the current stock is operating at or close to an optimal yield (FAO, 2005). In other words, the fishery is running at a level that provides the greatest socio-economic benefit, whilst taking into account the protection of the marine ecosystem (OECD, 2006).

However, the inference that a fishery is ‘sustainable’ is debatable and highly dependent on which of the numerous definitions of sustainability is being used (Poseidon Aquatic Resource Management, 2004). This issue can be particularly problematic when it comes to setting the sustainable catch limits used by many governments to prevent overfishing. For example, during the 1960s and early 1970s the South American anchoveta industry was operating at an all-time high level of catch, driven by increasing demand and the subsequent expansion of the fishing fleet

(IFFO, 2009b). Therefore the yields provided the fishing industry with an overly optimistic perception of the real sustainable abundance of the species, which led to ongoing exploitation of the anchoveta stocks (FAO, 2005). Despite warnings from the scientific community that this level of extraction was beyond carrying capacity, production continued to increase hitting an all-time high of 13.1 million tonnes in 1970 (FAO, 2005). This was followed by an ecological collapse that affected not only the stocks of anchoveta, but also the seabirds that relied on them as a source of food, the Peruvian economy that relied on the industry as a major source of export earnings and the feed producers that relied on this as a cheap source of oil and protein. This was an unsustainable outcome by any definition. Initially this was blamed on the occurrence of an unusually powerful El Nino event; a weather pattern that has a significant impact on the Humbolt current that is responsible for the highly fertile upwelling ecosystem off the coast of Peru and Chile. Although this played a role in the 1972 collapse, there was significant evidence to show that overfishing was also to blame (Pauly et al., 2002).

The Peruvian government responded by downsizing the fleet and closing off fishing grounds, however the industry struggled to recover for two decades (Laws, n.d). Since this time there has been extensive research to better understand the interaction between oceanography, fishery population dynamics and fishery economics (Pauly and Tsukayama, 1987), which has been used to establish management tools to ensure that the fishery can withstand shocks such as El Nino. These include maximum catch limits and tradeable quotas, which have helped to maintain a relatively stable anchoveta catch (7 million tonnes per year) over the past 30 years (IFFO, 2009b). This is of significance to the aquaculture sector as the South American industry is responsible for over 40 percent of the fish used for reduction purposes globally (FAO, 2012b), hence fluctuations in the supply of anchoveta have significant impacts on the availability and price of FMFOP on the global market (Nordahl, 2011). In 2009 the Association of Peruvian Anchovy Producers (APAP) announced that they were applying for certification from the world's leading sustainable seafood certification, the Marine Stewardship Council (MSC). Despite having the support of the likes of WWF, at the time of writing none of the anchoveta fisheries have been certified.

The other major criticism regarding the use of FMFOP relates to the social equity of taking a resource that theoretically could be used as a low-cost source of protein for direct human consumption, and feeding it to high-value species that are sold to the wealthy. However the majority of the species used are small, bony and oily (Pike and Barlow 2003), with the UN claiming that only 10 percent of fish used for reduction are marketable in large quantities as human food (FAO, 1986). As such, some claim that the aquaculture industry is adding to the supply of food for human consumption through the conversion of otherwise inedible proteins and fats into products that are demanded by the market (ref). An alternative explanation relates to the economic reality that suitable markets are located long distances from where the fish are landed. As such, the associated transport and storage costs increase the price of the final product beyond this consumer groups' ability to pay (Wijkström, 2009). Others claim that the anchoveta industry has actually improved the food security status of impoverished communities in South America through the provision of employment opportunities (Poseidon Aquatic Resource Management, 2004). This is not insignificant as the Peruvian industry alone currently employs around 40,000 fishermen, although this varies according to seasonal factors (Evans, 2010).

Regardless of these differences in opinion, the general concern regarding the use of wild capture fish resulted in pressure being placed on industries such as salmon to reduce their reliance on these as a source of feed. This led to the development of a the fish in fish out (FIFO) ratio which measured the live weight volume of wild fish needed to produce one tonne (live weight) of cultured fish harvested from aquaculture. There has been ongoing debate regarding how to calculate this, with suggestions put forward by academics (Tacon and Metian, 2009; Naylor et al., 2009) as well as various industry groups (Jackson, 2009; Carr, 2010). Not surprisingly the results obtained from these vary significantly. A brief review of these and the reasons for the variation will be presented in the following paragraphs.

The most widely used academic versions of the FIFO ratio are those developed by Tacon and Metian (2008), and a similar measure by Naylor et al. (2009). Both of these calculated the dependency ratio separately for FM and FO so as to take into consideration the fact that there is residual oil contained within the FO (Equation 2). To do this, the FO content of the FM (approx. 8%) is subtracted from the total FO requirements to get a more representative picture of the amount of forage fish needed to supply the FO (Equation 3). The Naylor version takes this one step further by adding up the reduction fish equivalent (RFE) for FM and the RFE for the additional oil (AO) to create a single FIFO value, as can be seen in Equation 4.

Unlike FCR, these measures take into account the variation in live weight by first calculating the reduction efficiency of the conversion of forage fish into FM and FO. This can vary significantly based on the species being used, the seasonal conditions as well as the efficiency of the reduction process itself, however it is generally accepted that the global average is 22.5 percent for FM and five percent for FO (Jackson, 2009). This is then used to calculate the second conversion of FM and FO into live weight fish equivalents.

$$RFE\ (_{FM}) = \left[\frac{Diet\ FM\ (g/kg)}{FM\ reduction\ efficiency\ (g/kg)}\ \right]\ x\ eFCR$$

Equation 2

$$RFE\ (_{AO}) = \left[\frac{Diet\ FO\ (g/kg) - (0.08 - Diet\ FM\ (g/kg))}{0.08}\ \ x\ eFCR\right] - \ [0.08 - RFE\ (fm)]$$

Equation 3

$$FIFO = RFE\ (_{FM}) + \ RFE\ _{(AO)}$$

Equation 4

Where:

FIFO	Fish in:Fish out
$RFE_{(FM)}$	Reduction fish equivalent (fishmeal)
$RFE\ _{(AO)}$	Reduction fish equivalent (additional fish oil)
$RFE\ ^{(FM)}$	Reduction fish equivalent (fishmeal)
Diet FM	Weight of fishmeal per kilogram feed
Diet FO	Weight of fish oil per kilogram of feed
eFCR	Economic feed conversion ratio
FM reduction efficiency	Yield of FM from raw material

All of these calculations attracted significant criticism for a number of reasons, the first of which is their assumption that all FM and FO used in the diets came from wild-capture fisheries. Given that approximately 25 percent of all FMFOP is estimated to come from the rendering of by-products from the processing of species that are caught or grown (aquaculture) for direct human consumption (Jackson, 2011), these calculations significantly overestimate the impacts on forage fisheries. This issue was addressed by the WWF Forage Fish Dependency Ratios (FFDR) that use a similar method to those described above, however only FM or FO derived from dedicated reduction fisheries are included in the calculation (Equation 5 and 6).

$$FFDR_m = \left[\frac{\%\ FM\ in\ feed\ from\ forage\ fisheries}{24}\right]\ x\ eFCR$$

Equation 5

$$FFDR_o = \left[\frac{\%\ FO\ in\ feed\ from\ forage\ fisheries}{5}\right]\ x\ eFCR$$

Equation 6

Where:

$FFDR_m$	Forage fish dependency ratio (meal)
$FFDR_o$	Forage fish dependency ratio (oil)
% FM in feed	Percentage of total fishmeal in the feed that comes from reduction fisheries
% FO in feed	Percentage of total fish oil in the feed that comes from reduction fisheries
eFCR	Economic feed conversion ratio

What all of these methods failed to account for was that some species have higher requirements for either FM than FO and vice versa. To explain the implications of this, take the example of salmon feeds that are on average contain 24 percent FO and 16 percent FM by weight (Tacon and Metian, 2008). Not only do they have a higher requirement for FO, but the yield of FO from the reduction process is significantly less (5%) than for FM (22.5%). The combination of these two factors means that more pelagic fish are needed to meet the FO requirements than to meet those for the FM.

In the process of creating the additional FO, there would be an excess of FM that is not used by salmon. In reality this excess would be used by another species, however this is not captured in the above calculations, which inadvertently assumes that the additional product is thrown away (Jackson, 2009). As such, if all the FIFO ratios for the various species were to be added up the total would be well in excess of the total amount of FM and FO that is physically available. Once again, this grossly overestimated the reliance of aquaculture on marine resources.

In recognition of this issue, Jackson (2009) from the International Fishmeal and Fish Oil Organisation (IFFO) took a more holistic view that calculated the FIFO ratios for a combination of several aquaculture species. From this he developed an alternative method that addresses the issue of double counting as described above (Equation 7). It does not however account for the FMFOP that are derived from sources other that dedicated reduction fisheries.

$$FIFO = \left[\frac{Level\ of\ FM\ in\ diet + level\ of\ FO\ in\ diet}{Yield\ of\ FM\ from\ wild\ fish + yield\ of\ FO\ from\ wild\ fish}\right]\ x\ eFCR$$

Equation 7

Where:

FIFO	Fish in:Fish out ratio
FM in diet	Inclusion level of fishmeal in the feed
FO in diet	Inclusion level of fish oil in the feed
Yield of FM	Yield of fishmeal from raw material
Yield of FO	Yield of fish oil from raw material

However, this too has been criticised, along with all the other measures for failing to take into account the nutritional value of the species under production (Crampton et al., 2010). This focus on weight as the basis of comparison not only ignores the value of specific marine oils and proteins to human nutrition but also creates an un-level playing field for species with a higher fat content (Crampton et al., 2010). For this reason, yet another alternative known as the marine nutrient dependency ratio

(MNDR) was developed to provide a better indication of nutritional values (Carr, 2010). Once again, oils and proteins are accounted for separately creating one calculation for marine oil dependency (MODR) as shown in Equation 8 and another for marine protein dependency (MPDR) in Equation 9. This can also be altered to exclude FMFOP that are derived from sources other that reduction fisheries, as done by Ytrestøyl et al. (2011).

$$MODR = \left[\frac{FoFeed + (FMfeed\ x\ FoFM)}{OilSalm}\right]\ x\ eFCR$$

MODR Marine Oil Dependency Ratio

FoFeed Concentration of fish oil in the feed (%)

FMfeed Concentration of fishmeal in the feed (%)

FoFM Concentration of oil in fishmeal (as a proportion)

eFCR Economic Feed Conversion Ratio

OilSalm Concentration of oil in the salmon on whole fish basis (%)

Equation 8

$$MPDR = \left[\frac{FMfeed\ x\ PrFM}{PrtSalm}\right]\ x\ eFCR$$

MPDR Marine Protein Dependency Ratio

FMfeed Concentration of fishmeal in the feed (%)

PrFM Concentration of protein in fishmeal (as a proportion)

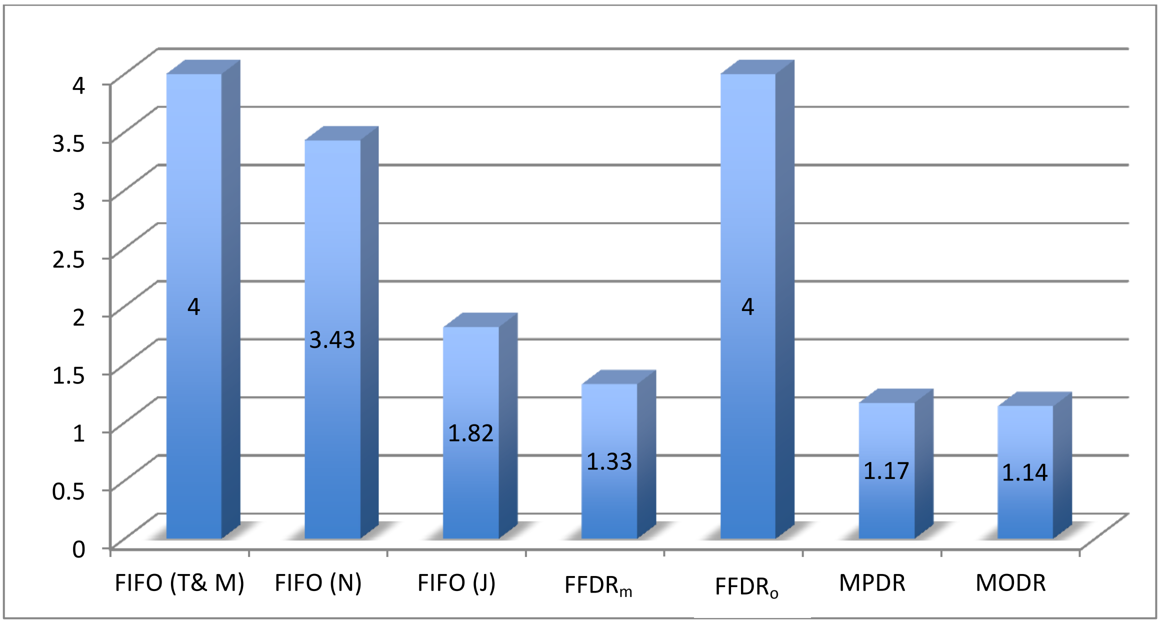
eFCR Economic Feed Conversion Ratio

PrtSalm Concentration of protein in the salmon on whole fish basis (%)

Equation 9

Not surprisingly this approach has also attracted criticism since it was developed by an employee from EWOS, the world's second largest producers of salmon feeds. Following the approach taken by Carr (2010), all of the above mentioned metrics were calculated to demonstrate the variation between these measures, with the results presented in Figure 13. The exact numbers used in these calculations were taken from Tacon and Metian (2008), a summary of which can be found in Table 2.

Figure 13: Results from the various measures of marine resource utilisation (per kilogram of salmon), 2007



T&M = Tacon and Metian, 2008; N = Naylor, 2008; J = Jackson, 2009

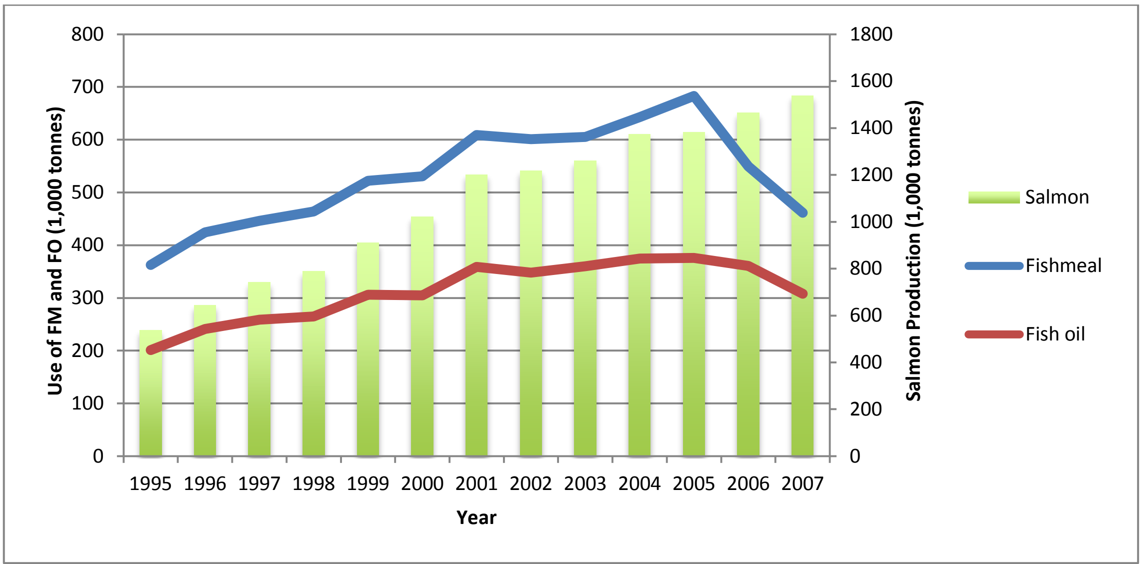
Table 2: Values used to calculate various measures of marine resource utilisation

Measure	Global Average
Total Production (t)	1,538,000
eFCR (kg/kg growth)	1.3
Total feeds used (t)	1,923,000
Total FM used (t)	461,500
Total FO used (t)	307,700
FM yield (%)	22.5
FO yield (%)	5

Source: Tacon and Metian (2008)

As previously mentioned, there is significant variation between the results obtained from the various measures. Despite this, regardless of which is used salmon aquaculture has experienced a decline in the utilization of marine resources per kilogram of fish produced over the past few decades. This is based on the fact that there have been changes to two of the key variables in all calculations, with FCR decreasing and reduction efficiency increasing over this time (Ytrestøyl et al., 2011). This is further evidenced by the fact that whilst the global production of salmon has increased from 537Mt in 1995 to 1538 in 2007, its use of FM and FO has simultaneously declined.

Figure 14: Estimated global demand for FM and FO from compound salmon feeds



Source: Data sourced from Tacon and Metian, 2008

Although the original goal behind the FIFO ratio was to serve as a proxy to demonstrate the relative ecological stress that a particular aquaculture system placed on wild-capture fisheries, it has been economics that has driven the industry to take action to improve these (Tacon and Metian, 2008). For although the classification of the reduction fisheries as fully exploited does not indicate overfishing in an ecological or biological sense, it does clearly state that these fisheries are at full production capacity. The implications of this on industries such as salmon that rely on these resources is that future growth is limited by the availability of a resource that is confined by ecological or biological limits.

Around the late 1980s it was recognised that this limited supply, coupled with the increasing demand for FMFOP was a serious threat to the industry. This led to predictions that this situation would ultimately lead to a cost-price squeeze that could constrain future growth, a situation coined as the 'fishmeal trap' (Wijkström and New, 1989; New and Wijkström, 1990). To a certain extent, the aquaculture industry has managed to avoid the fishmeal trap through the adoption of a range of technological and biological advancements that will be discussed in the following sections of this chapter. These include but are not limited to a combination of improvements made to fish nutrition, raw material selection, feed production, selective breeding and on-farm management. The role that each of these have played will be discussed in further detail below.

3.3 Drivers of Efficiency

3.3.1 Fish Nutrition

One of the key drivers of both of the above mentioned forms of efficiency has been the ongoing research undertaken to better understand the specific nutritional requirements of salmon and the metabolic factors that affect the digestibility of feeds. As such, the feed industry has evolved to take a very scientific approach to feed formulation that is focused on achieving the correct mix of macro and micronutrients (Intrafish, 2011). Macronutrients are the lipids, carbohydrates and proteins that serve a range of functional roles, including the provision of energy. Micronutrients such as minerals and vitamins on the other hand are required in much smaller volumes and although they do not provide energy, they are vital to the growth and general well being of the fish (National Research Council Staff, 1993).

Studies into salmon metabolism have found that unlike terrestrial animals and herbivorous fish that derive the bulk of their energy from carbohydrates, carnivorous species such as salmon are more reliant on proteins and lipids as a source of energy (Sargent et al., 2002). The reason for this is that carbohydrates are not well tolerated by salmon and have been shown to play a role in the development of conditions such as enlargement of the liver (National Research Council Staff, 1993), or prolonged postprandial hyperglycaemia (Panserat and Kaushik, 2002). Therefore their use in feeds is limited to binders and fillers that enhance the physical characteristics of the feeds rather than for nutritional reasons (Storebakken, 2002). This translates into higher prices since proteins and fats tend to be more expensive in comparison to carbohydrates, making aquafeeds some of the most expensive animal feeds on the market (Bureau, 2006).

In contrast, salmon are able to digest protein more efficiently than other species due to the way in which they metabolise the nitrogen contained within proteins. The majority of the nitrogen excreted as a result of protein metabolism in salmon is in the form of ammonia not urea or uric acid as is the case with birds and mammals. Since the conversion of ammonia to urea requires energy, the net energy gain from the consumption of proteins is higher (Halver and Hardy, 2002). In addition to their role in providing a highly digestible source of dietary energy, proteins are also required for a range of vital functions including the synthesis of muscles, hormones, neurotransmitters and metabolic enzymes (Takeuchi, 2007). Therefore failure to feed adequate amounts of protein can result in serious consequences for the general health of the fish. It is equally as important not to provide too much protein because unlike carbohydrates and fats, excess protein is not stored but rather it is excreted as nitrogen as ammonia. This represents not only a waste of economic resources, but it also contributes to eutrophication of the surrounding water body. Therefore, correct protein nutrition is important for animal performance, cost efficiency and the natural environment (FAO, 2004).

The nutritional status of salmon is not only influenced by the amount of protein in the diet, but also the composition of the molecular building blocks from which proteins are made, otherwise known as amino acids (AA). There are approximately 200 kinds of AAs in nature of which 20 are used to synthesize proteins (Takeuchi, 2007). All living organisms require a particular suite of these in order to maintain health, some of which can be synthesized endogenously and others that must be provided by the diet. The latter of these are referred to as *essential AA*s (EAA) of which fish, including salmon have an absolute requirement for ten of them (threonine, valine, leucine, isoleucine, phenylalanine, methionine, tryptophan, arginine, histidine, lysine) (Jobling, 2010c). Deficiency in all or one of these can result in health problems, for example the formation of cataracts that can occur due to methionine deficiency (National Research Council Staff, 1993).

The last of the macronutrients are lipids, more commonly known as fats or oils. These substances have almost double the caloric energy of proteins and carbohydrates, which have made them a key ingredient in modern salmon feeds that are very energy dense (Naylor et al., 2009). As well as being a source of dietary energy they also provide important building blocks for cell membranes and act as vectors for a range of fat-soluble nutrients and pigments (Bell and Koppe, 2011). Similar to proteins, lipids are comprised of a series of smaller molecules known as fatty acids (FA), some of which are considered to be essential (EFA), indicating that they must be provided by the diet. However, unlike EAA that are widely available in a range of materials, a number of the EFAs required by salmon are finite in nature due to the fact that the major source of these are the pelagic fish discussed above. These FAs are not only vital to the health and growth of the salmon themselves, but are the key reason why salmon is recommended for human consumption by nutritionists and other health professionals throughout the world. In fact this issue is at the core of the rift that exists between the three key disciplines of relevance to this study. Before explaining why this is the case, a brief overview of these substances and their relevance to salmon and the people that consume them will be provided.

FA are organic molecules that have a hydrocarbon chain as their backbone. These are categorised in a number of ways based on the length of their chain and the presence of double bonds between carbon atoms within it. The length of chain varies from *short chain* FA (SCFA), which have between four and six carbon atoms, to *very long chain* FA (VLCFAs) that are greater than 22 carbons. In regards to the presence of double bonds, FA fall into one of two categories commonly referred to as *saturated FA* (SFA) and *unsaturated FA* (UFA). Those that are saturated have no double bonds and are solid at room temperature, whilst UFAs are liquids that have at least one double bond. These are further classified as either *monounsaturated FA* (MUFA) or *polyunsaturated* FA (PUFA) depending on the number of double bonds within their chain. In scientific shorthand, FAs are identified using a series of three numbers. The first refers to how many carbon atoms in the chain, and the second number to how many double bonds. For example 18:0 refers to a FA that is 18 carbons in length, with zero double bonds in its chain, making it a SFA. The third number refers to the final classification that is only of relevance to UFAs that is based on where in the carbon chain the first of these double bonds is located. This gives rise to the terms omega-3 (n-3), omega-6 (n-6) and omega-9 (n-9).

Both omega-3 and omega-6 are EFAs in the human diet. This is also the case for the majority of other animals, including salmon, as only plants are able to synthesize these substances endogenously (Gropper et al., 2005). There are three particular molecules that are vital for normal growth and development of fish and humans, these are eicosapentaenoic acid (EPA, 20:5 n-3) and docosahexaenoic acid (DHA, 22:6 n-3) from the omega-3 class and arachidonic acid (ARA, 20:4 n-6) from omega-6. These are important in a range of physiological functions in the organisms that consume them, two of which are of particular importance.

The first relates to the structural and functional integrity of cell membranes. Every cell in the body contains a phospholipid bilayer, which acts as a protective barrier that helps to control the flow of nutrients and other metabolites into and out of the cell. As the name suggests this layer is comprised of a number of lipids including EPA, DHA and ARA. The concentration of these varies between species, with fish having higher concentrations of omega-3s, in particular DHA, whilst terrestrial animals tend to have more ARA (Sargent et al., 1999). It also varies between the cells found in different tissues within the same organism, with DHA being prominent in cells found in the neural (brain and retina), sperm and heart cells of terrestrial animals (Bell & Koppe, 2011). Due to the importance of DHA to these cells that are found in tissues that perform key physiological functions, a deficiency in these FA can have detrimental health implications. This is well documented in human clinical studies where EPA and DHA deficiency has been shown to increase the risk or severity of cardiac disease (von Schacky, 2006), inflammatory diseases and autoimmune diseases (Simopoulos, 2002) as well as psychiatric disorders like depression and dementia (Freeman, 2000). Conversely, people suffering from such disorders have shown to respond positively to supplementation with these substances (Nichols et al., 2010).

There are actually another two PUFA that are considered to be essential; linoleic acid (18:2, n-6) and α-linolenic (ALA, 18:3 n-3). Unlike the above-mentioned FA, these are available from both marine and terrestrial plants, most notably linseed and canola (rapeseed) (Gropper et al., 2005). The drawback to these is that despite being EFAs they are not actually in the molecular form that is required by animals to perform the important physiological roles described above. As such, they need to be converted into the bioactive LCPUFA products, which for linoleic acid is ARA and for ALA it is EPA and DHA (Bell and Koppe, 2011). As can be seen from the scientific shorthand, both linoleic acid and ALA are slightly shorter in length and have less double bonds than their bioactive counterparts. Both humans and salmon are able to perform the transformation of these through the process of elongation (add carbons to the chain) and desaturation (insert double bonds). However this process is generally very inefficient with studies of salmon (Sargent et al., 2002), as well as humans (Pawolsky et al., 2001) indicating that it is not possible to meet the dietary requirements of these EFAs without significant dietary supply.

Despite these findings, the aquafeed industry has made significant breakthroughs in utilizing plant-based oils to replace a substantial proportion of FO whilst demonstrating that there are no negative implications for the health and growth rates of the fish (Watanabe, 2002). However, as the saying goes you are what you eat, and this is certainly the case in regards to salmon. The FA profile of the aquafeeds is generally reflected in the FA profile of their flesh (Lovell, 2002), which is then passed on to the humans that consume them. For example, a study conducted by Seierstad et al., (2005) compared the human health effects of eating salmon that were fed different diets that contained high (100%), medium (50%) and low (0%) amounts of fish oil, with the remainder of the oil provided by rapeseed. The results indicated that the serum FA profiles of the 60 patients that took part in the study mirrored those of the diets that the fish were fed in regards to total omega-3 levels.

It is for this reason that there is conflict between the goals of sustainable production and consumption in regards to salmon aquaculture. For whilst there is concern from a production perspective regarding the sustainability of utilizing wild capture fish to produce the feeds, salmon that are fed these ingredients are encouraged from a consumption perspective on account of the associated health benefits. Then there is the economic objective to create a product that meets market demand for these oils using the cheapest suitable feedstock. As such these areas continue to be widely researched as the industry seeks ways in which it can simultaneously address all three of these concerns. Some commonly used alternatives will be discussed in more detail in section 3.3.3 of this chapter.

In addition to the research done on the role of various nutrients in salmon, a number of anti-nutritional factors (ANF) have also been discovered. These substances are defined as endogenous compounds found in the raw materials that are used to make the feeds that may reduce food intake, growth, nutrient digestibility and utilization, affect the function of internal organs or alter disease resistance (Krogdahl et al., 2010). The majority of these are found in materials of plant origin and are considered to be the major limiting factor preventing their use in aquafeeds and other compounded animal feeds (Tacon, 1985). Two substances commonly found are protease inhibitor that interferes with the enzymes required to digest proteins and phyates that affect mineral utilisation (Francis et al., 2001).

There has also been significant work done to match the nutrient composition of the formulated feeds to the exact requirements of salmon at particular life stages. As a result of the better understanding of this relationship, salmon are fed a number of different feeds throughout their lives. For example, broodstock feeds are fortified with specific nutrients to ensure they produce high quality eggs (Jobling, 2010c) whilst the feeds used in the fingerling phase are higher in protein to provide the building blocks needed for this phase of rapid growth (Hardy and Barrows, 2002). For a completely different reason a higher level of FA is included in finisher diets that are used before harvest so as to ensure the flesh has the desired organoleptic characteristics and omega-3 content as desired by the end consumer (Jobling, 2010c). This understanding of nutrition through the life stages has therefore allowed the aquafeed industry to be more strategic with their use of FO to ensure they get maximum benefit out of this finite resource.

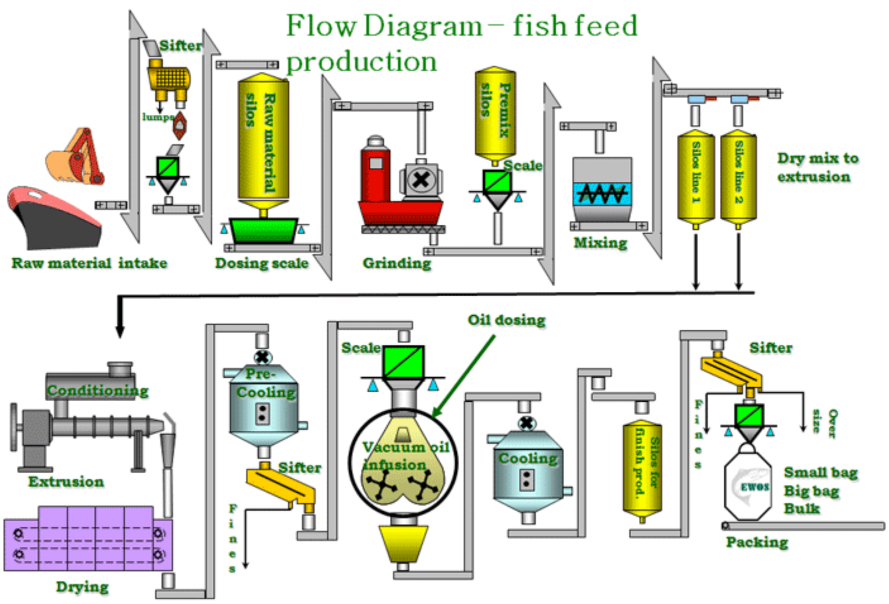
In more recent times, research has followed trends in human nutrition that have focused on the inclusion of 'functional' foods. This includes the use of prebiotics and probiotics that play important roles in immunity and digestive health of the fish. Probiotics introduce beneficial strains of bacteria into the intestinal tracts of the fish that reduce the abundance of pathogenic bacteria through competitive exclusion (Gatlin, 2002). Prebiotics on the other hand are non-digestible food ingredients that stimulate the growth of health promoting bacteria in the intestinal tract, which further aids in the prevention of infection (Rana and Hasan, 2009). This preventative approach to fish health has not only improved growth rate, but has also reduced the need for antibiotic use (Hoffman, 2009).

3.3.2 Feed Production

In the early days of salmon aquaculture, feeds were made on-farm by the individual producers based on a crude mixture of readily available materials (Asche and Bjorndal, 2011). At this earlier time, approximately 20% of the feeds used in sea cage operations were lost to the surrounding environment resulting in a high FCR and significant environmental damage (Beveridge, 1987). As the industry grew, these wet feeds were gradually replaced with commercialised dry pellets that were made according to specific recipes based on the nutritional requirements of the fish as described above (Hardy and Barrows, 2002). When developing these recipes, producers were faced with significant technical challenges as these pellets needed to meet a number of economic, nutritional and physical objectives (Hardy and Barrows, 2002). Firstly, the feeds had to provide the correct mix of nutrients in a format that was highly digestible to the fish. This had to be done using a range of raw materials that varied throughout the year based on availability and price. Secondly, the pellets also needed to be physically strong enough to withstand handling throughout the supply chain, as well as the mechanical force of the machines used to distribute the feeds on-farm. Once in the water, they had to sink at the correct rate and remain intact to ensure the fish were able to consume the maximum amount so that wastage and the associated environmental pollution was minimised. Finally, the pellets needed the right mix of organoleptic properties (taste, smell, texture) so the fish actually ate them.

The ability of the industry to address these issues was made possible when conventional steam pelleting was replaced by extrusion technology in the 1990s (Tacon, 2005). Extrusion involves the creation of a dough mixture from the raw materials that is steam conditioned and forced through a small hole at high temperature and pressure. In the process of extrusion the starch that is present in the raw materials is gelatinised, making the pellets more stable in water as well as increasing the bioavailability of carbohydrates whose digestibility improves when cooked (Lovell, 2002). The digestibility of the feeds is further enhanced through the destruction or inactivation of many of the anti-nutritional properties of the raw materials (Tacon & Jackson, 1985). In saying this, this process also destroys some important heat sensitive nutrients such as vitamins A, E, C and some forms of vitamin B that then need to be replaced at a later stage in production (Riaz et al., 2009). A summary of the extrusion process can be seen in Figure 15.

Figure 15: The extrusion process



Source: Cermaq, 2010

However, the greatest benefit of extrusion technology has been the ability to increase the lipid content of the feeds, and in doing so increase the energy density (Tacon, 2005). This is due to the entrapment of water vapour within the pellet during the extrusion process, which once dried creates air pockets. These allow the pellet to act like a sponge when they are vacuum coated with oil towards the end of the process and absorb much higher levels of fat than with steam pelleting (National Research Council Staff, 1993). This has allowed the lipid content of feeds to increase from around 10% in 1985 to 35-40% in 2005 (Tacon, 2005), with every 1% increase in the inclusion rate of lipids translating into a 1% reduction in organic waste (Asche and Bjorndal, 2011). Not only has this improved productivity, but the air pockets give the pellet greater buoyancy in water, slowing down the rate at which it sinks and giving the fish adequate time to eat them (Hardy and Barrows, 2002).

3.3.3 Alternative Raw Materials for Feeds

Given the technological and biological advancements described above, the raw materials used in feeds are now seen as a combination of the individual nutrients of which they are composed. This approach has allowed the industry to reduce their reliance on FMFOP through the utilisation of 40 essential nutrients that are found in a range of raw materials (Tacon, 2010). These include a number of alternative marine sources as well as those from terrestrial origins including plants and the by-products from the production of meat for human consumption. A summary of the alternative sources of proteins and lipids being used to produce salmon aquafeeds will be discussed below, including the economic, environmental and nutritional factors that determine the degree to which they can be utilised now and in the future.

3.3.3.1 Alternative Marine Resources

Materials derived from the by-products of seafood processing and fisheries by-catch are portrayed as offering great potential for inclusion in aquaculture feeds (Hardy et al., 2005). The first of these refers to the rendering of trimmings (e.g. heads, frames, bones and viscera) from the processing of seafood that is destined for human consumption. Although accurate estimates are difficult to obtain, the IFFO estimates that five and a half million tonnes, or 25 percent of the total inputs used to make FMFOP each year come from these sources (Jackson, 2011). Not only does this take pressure off wild-capture fisheries by providing an alternative source of marine proteins and oils at a cheaper price, it also utilizes a 'waste' that would otherwise be discarded with the potential to do environmental harm. Therefore they offer a suitable alternative, so long as care is taken to store and treat them properly to avoid a loss of quality or the formation of toxic substances (EC, 2005).

The second option refers to the utilization of the estimated seven million tonnes of by-catch (FAO, 2010) from wild-capture fisheries. Despite the intuitive appeal of this option from an environmental perspective, there are a number of barriers that prevent this from being implemented at a large scale. These relate to the commercial aspects of storing and transporting the fish to a processor (Clucas, 1997) and having a consistent supply to justify the significant capital expenditure required to process these into FMFOP (Olsen et al., 2011). This refers not only to the reliability of volume, but also quality as the species contained within the by-catch are highly variable resulting in inconsistent lipid quality and quantity (Batista, 2007).

Another alternative is to utilize marine creatures from further down the food chain such as small crustaceans from the copepod genus, krill (euphausids) and mesopelagic fish (Olsen et al., 2011). The only commercial fisheries currently in existence are for krill stocks from the Antarctic Ocean (*Euphausia superba*) and to a lesser extent those from the Pacific (*Euphausia pacifica*). These creatures offer a balanced package of marine proteins, phospholipids and DHA as well as astaxanthin, a valuable carotenoid that provides the orange pigment that is of high value for the salmon industry (Storebakken, 1988). However the use of these for reduction purposes is even more controversial than pelagic species due to the vital role they play in the marine food web (Mente et al., 2006), and the potential impacts that overfishing may have on the populations of predatory species which include whales, penguins and seals (CCAMLR, 2012). The tight meshed nets used to catch the krill are also problematic since they result in a high amount of by-catch, as well as an increase in fuel use on account of the additional drag (Nordhahl, 2011). For these reasons there has been a ban placed on extracting these resources by many governments, with several parties trying to implement a total ban (Olsen et al., 2011).

The krill fisheries in the Antarctic have been operating since the 1970s to a supply a range of human and industrial products, with more recent demand coming from the aquaculture sector and the nutraceutical industry (Parker and Tydemers, 2012). There are limitations on the future growth of this fishery as it is protected by the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) Treaty. This came into force in 1982 in response to the increasing commercial interest in Antarctic krill, with sustainable catch limits (quotas) imposed as part of the associated management plan. Based on scientific assessments of the stocks of krill and to a lesser extent their predators, the current sustainable catch limit is set at 620,000 tonnes per annum (CCAMLR, 2012). Interestingly the fishery has only ever reached a third of this allocation (Starling, 2012), which presents an opportunity for future expansion (Nichols and Foster, 2003). This opportunity was seized by Norwegian company Aker BioMarine, who in 2008 revolutionized the industry with the release of their *Saga Sea* trawler. This 'factory trawler' has the capacity to catch and process the krill at sea to create a range of dietary supplements for human consumption. In 2010 they were not only the first krill fishery to get MSC certified, but they were in fact first reduction fishery which has opened up new opportunities for sustainably sourced marine proteins and oils.

3.3.3.2 Plant Based Alternatives

Plant based alternatives to FM and FO are seen to offer significant benefits in that they are more abundant, inexpensive and able to be sourced from a greater number of localities (Aslaksen et al., 2007). They are also seen by some to be more sustainable on account of the fact that their sustainable yields are much easier to estimate and manage than those of wild-capture fisheries (Gatlin et al., 2007). However it should be noted that there are significant environmental costs associated with the fertilisers used to grow the crops, and many of the on-farm activities challenge the concept of these being sustainable choices. Crops that are commonly used as raw materials for salmon feeds include oilseeds (canola, sunflower), legumes (soy, lupins) and cereal grains (wheat, corn) (Hardy et al., 2001), all of which have certain chemical characteristics that limit their ability to fulfil the same role as fisheries-derived products (Gatlin et al., 2007).

As previously mentioned, one of the major limitations associated with materials from terrestrial plants is the presence of ANFs. Whilst heat-labile substances such as protease inhibitors and lecithin are able to be eliminated through modern feed processing techniques, other such as indigestible oligosaccharides, tannins and phytates are more difficult to inactivate (Aslaksen et al., 2007). These require additional treatment, including fermentation or the use of exogenous enzymes to break the substances down. The latter has been used to treat soy by either pre-treating the materials prior to inclusion in the diet or by supplementing the diet with the necessary enzymes. Both of these methods have been shown to be effective in reducing phytase concentrations in CSP, resulting in improved growth performance in salmon (Carter and Sajjadi, 2011). An alternative approach has been to selectively breed commonly used crops such as soybeans and canola so to contain less of these ANFs (Krogdahl et al., 2010). Conversely, attempts are also being made to selectively breed fish that are able to tolerate higher amounts of these substances (Overturk et al., 2004).

The other major issue is the nutritional composition of many of these materials, in particular the AA and FA profiles. In regards to protein, many of the commonly used grains and oilseed are lacking in one or more of the EAA. As a general rule, grains tend to be low in lysine and threonine, whilst legumes are deficient in cysteine and methionine (Gropper et al., 2005). To overcome this, a combination of materials is used and supplemented with varying amounts of FM and amino acids to ensure that the requirements for all 10 EAAs are met (Hardy and Barrows, 2002). Products that have undergone further processing such as gluten meals derived from wheat or corn gluten and CSP offer a better package of digestible AA, however these tend to be more costly (Gatlin et al., 2007). Although there has been limited success with salmon feeds that have completely replaced FM with plant-based proteins, replacement levels of up to 70 percent are generally accepted as being well tolerated (Pratoomyot et al., 2011).

Vegetable oils (VO) have received considerable attention in recent years on account of the rising costs of FO. In addition to their comparatively lower costs, they also contain lower concentrations of organic pollutants such as dioxins, furans and polychlorinated biphenyls (PCB) that are commonly found in fisheries-derived products (Miller et al. 2011). The major limitation with VO is that although they are a good source of n-6 and n-9 PUFA, they are often poor sources of n-3. There are some exceptions, most notably linseed (or flax), which contains up to 35 percent ALA (18:3, n-3) (Tocher et al., 2011), and to a lesser extent canola (6-13% ALA) (Turchini and Mailer, 2011) and soy (4-10% ALA) (Brown and Hart 2011). There is research that is looking at the potential to overcome this issue by genetically modifying (GM) crops to produce EPA and DHA. These include but are certainly not limited to the efforts being made by GM majors such as Monsanto (canola), Dupont (soy) and BASF (mustard) (Miller et al., 2011). On a more local level, CSIRO have identified genes from microalgae that produce EPA and DHA and inserted them in oilseeds that are then able to synthesize their own LCPUFAs (CSIRO, 2012). The results of the above mentioned studies have been promising, with the GM oilseeds showing levels of EPA that are comparable to marine sources, although work is still needed to obtain adequate levels of DHA (Nichols et al., 2010). Despite the promise of these developments for both environmental and nutritional outcomes, a major limitation is the adverse consumer perception to GM as well as the laws prohibiting their use (Wijesundera et al., 2011).

3.3.3.3 Terrestrial Animal By-Products

Of the 708 million tonnes of animal feeds produced in 2009, only four percent (28Mt) was used for aquaculture, with the remaining 96 percent comprised of feeds used for ruminants (25%), pigs (30%) and poultry (41%) (Tacon, 2010). As such the salmon industry faces significant competition for many of the above-mentioned plant proteins that are also commonly used in animal feeds, as well as for direct human consumption.

However a number of terrestrial animal industries are also the source of cheap, high quality proteins that have a balanced AA profile. Until recently animal fats were not used in aquafeeds as the digestibility was thought to be poor, however this has since been revised with considerable evidence to show that inclusion rates of 30-50 percent of total lipids has no adverse effects on fish health, growth rate or quality of the flesh (Bureau and Meeker, 2011). As such, these materials have been identified as being a key source of proteins and oils to avoid the fishmeal trap (Tacon, 2010).

Poultry offal meal (POM) is made from the materials removed from the poultry carcass before being sent to market, excluding feathers. These products are high in digestible protein (58%) as well as oils (13%) (Hardy and Barrows, 2002). The other product from the poultry industry is hydrolysed feather meal that contains reasonable levels of digestible protein, although these are not the same quality as those found in POM (Hardy et al., 2001). Despite being a good source of protein, the FA profile is not ideal as it contains more SFA and omega-6s, with limited omega-3s. The red meat sector also provides a range of products that are a good source of high quality AA, including meat meal that is made from dried mammalian tissues as well as meals made from the proteins contained within bones and blood (Hardy and Barrows, 2002). Similarly to the fats from the poultry sector, tallow (animal fat) does not have a favourable FA profile as it is primarily SFA with smaller amounts of MUFA and PUFA.

Previously, the use of these materials in animal feeds was widely practiced, however this all changed following the outbreak of bovine spongiform encephalopathy (BSE) that affected cattle throughout the UK and parts of Europe in the 1990s. Whilst the exact nature of the transmissible agent is not well understood, it is widely accepted that the cause of these outbreaks was the feeding of rendered ruminant products that contained BSE-infected products to the cows (CDC, 2012). As such, countries around the world have introduced regulations that prohibit the use of rendered animal products in animal feeds. In countries such as Australia this ban applies only to the feeding of rendered animal products to ruminants, however in Europe and the UK this extends to the feeding of these materials to other species, including fish (Hard, 2003). This is evident when examining the composition of salmon feeds used in the four big producing nations (Table 3), with those used in the UK and EU containing no products derived from animals.

Table 3: Inclusion rates (% weight) of feed ingredients from different sources

Source	Norway	UK	Canada	Chile
Fisheries	58	66	32	43
Crops	42	34	48	42
Poultry	0	0	20	15

Source: Data taken from Pelletier et al., 2009

3.3.3.4 Single Celled Organisms (SCO)

This group includes algae, bacteria and yeasts that, depending on the strain used, can contain between 40 to 80 percent protein (Hardy et al., 2001). Algae and bacteria sourced from the marine environment also hold significant promise as a source of EPA and DHA since it is these exact organisms that are the primary producers of omega-3s in the marine food web (Miller et al., 2011). Despite the identification of a range of SCOs that contain these valuable omega-3 FA, not many of these have been produced at a commercial scale on account of the costs involved in their production (Tacon, 2010). Similar issues have been encountered by the biofuel industry that is investing heavily in solving this problem, with opportunities for synergies between the two industries as breakthroughs are discovered in the future (Naylor et al,. 2009). One species that has attracted significant attention in recent years is thraustochtrids on account of its relatively high DHA and carotenoid content (Gupta et al., 2012), but also its ability to consume organic carbon from industrial waste streams (Fan et al., 2001). Martek, the world's leading algal oil manufacturer is utilizing these organisms to produce their *DHAgold*™ product (17% DHA) that is being used in a range of animal feeds, including those used in the aquaculture sector (Martek, 2012).

Other companies operating in this field include many of those that are active in research for GM crop including Dupont who have used a strain of the *Yarrowia* *lipolytica* yeast to develop their New Harvest™ omega-3 supplement that contains 50 percent EPA (Dupont, 2012). There are obvious environmental benefits to this approach as these microorganisms do not require land or fertilisers as terrestrial based plants do and can in fact be grown in harsh environments that other aquaculture species would not tolerate (Miller et al., 2011).

The above-mentioned list of alternative feed materials is by no means exhaustive, with an estimated 18,000 individual feed ingredients available for fish nutritionists to experiment with (Hardy and Barrows, 2002). In addition to the advancements that have improved the efficiency of salmon production through modifying feeds, there have also been significant developments in regards to the fish themselves and the animal husbandry techniques used on-farm. These will be discussed in the following sections.

3.3.4 Genetics and Selective Breeding

The reduction of FCR has also been indirectly influenced through selective breeding programs that have utilised genetic variation amongst salmon populations to breed for favourable traits, in particular growth rate. The correlation between growth rate and FCR in salmon was first discovered when Grisdale-Helland and Helland (1998) compared Atlantic salmon that were the fifth generation of fish selectively bred for enhanced growth rate, to those from the wild. Their findings were then validated by Thodeson et al. (2009), who found that the populations selectively bred for growth rate had a significantly lower intake of protein and energy per kilogram of bodyweight gain. From their studies they concluded that breeding programs focused on growth rate indirectly increased FCR by 25%. Growth rate continues to be the focus of numerous selective breeding programs, and as such there is opportunity for further improvements in feed utilisation. This includes Norwegian based Aqua Gen who are working in cooperation with national and international research institutions to utilise their expertise and extensive collection of genetic material to deliver productivity gains (AquaGen, 2008).

Opportunities to achieve productivity improvements through selective breeding will be further enhanced with the release of work being undertaken by the International Collaboration to Sequence the Atlantic Salmon Genome (ICSASG). This project began in 2010 with the aim to fully identify and physically map the genome sequence for Atlantic salmon. This is intended to provide biological information to assist those working with both wild and farmed salmon populations to better manage their stocks. As part of the research, they hope to also identify genetic markers that are linked to production traits that are of economic importance including growth rate and feed efficiency (Davidson et al., 2010). The project is now in its second phase which is due to be completed by the end of 2012.

Research is currently underway that is looking to breed transgenic fish, including salmon. This is predominantly focused on improving growth rate and altering metabolic pathways to allow for increased endogenous synthesis of EPA and DHA (Jobling, 2010c). Although progress has been made in the laboratory, to date nothing has been commercialised due to concerns regarding the unknown consequences of this on wildlife, ecosystems and human health (Curieux-Belfond et al., 2009). One of the most advanced attempts has been made by AquaBounty Technologies, a biotechnology company that is developing GM salmon, trout and tilapia that are designed to grow faster (AquaBounty, 2012). Earlier this year (2012) the company sumitted an application to the USA Food and Drug Administration (FDA) to get approval to market their engineered Atlantic salmon that contains a gene from the Chinook salmon, which they claim doubles the growth rate whilst not posing any risk to human health. This is currently under review by the FDA, although this has been met by serious consumer lobbying against it being approved.

3.3.5 Feed Management

Feed allowance and frequency of feeding play an important role in determining feed efficiency (National Research Council Staff, 1993). As such, the adoption of feed management systems that control the amount of feed given to the fish have also helped to achieve the optimal conversion of feed into flesh (Dunn, 2008). The first advancement took place when hand-feeding regimes based on feed tables and the experienced eye of the feeder were replaced with automated feeding systems such as hoppers and robot feeders. More recently this has been taken a step further to include feed monitoring technologies that are sensitive to the actual feeding behaviour of the fish. This includes techniques used to monitor the presence of waste pellets below the feeding zone as an indicator of fish satiety or through the use of hydroacoustics to monitor sounds that are characteristic of eating behaviour before, during and after feeding such as suction or specific swimming movements (*ibid)*. Regardless of the exact system in place, these allow producers to respond to changes in feeding behaviour that are otherwise difficult to predict due to a range of environmental and physiological factors (Beveridge, 2004) and match their feeding regimes to ensure maximum feed utilisation.

3.3.6 Control of Environmental Variables

Feeding behaviour is determined by number of environmental conditions, most notably water temperature and water quality (Beveridge, 2004). The temperature of the water has a significant impact on salmon as they are poikilothermic, meaning their body temperature varies according to their surroundings. There are noticeable differences that occur when the fish are outside of their thermal tolerance range including feed intake and growth rate (Jobling, 2010c). Temperature also affects the amount of energy derived from the lipids contained within the feeds that are more digestible at higher temperatures (Bell and Koppe, 2011). In regards to water quality, saturated oxygen levels are the most relevant to feeding behaviours, with intake dropping off dramatically once oxygen saturation drops below 65-75 percent (Jobling, 1997).

Improvements in the monitoring systems at hatcheries have allowed producers to modify the temperature and oxygen levels to achieve optimal feed intake, nutrient absorption and growth rate. There is far less ability to control these parameters at the sea cage stage other than ensuring that sites selected have the correct mix of climatic and oceanographic characteristics that meet the requirements of the fish. It is possible to artificially oxygenate the sea cages, however this is generally only practiced in times when oxygen levels are very low and there is a high risk of death (D. Miedecke, Pers Comm., July, 2012)

3.4 Efficiency Gains in the Tasmanian Salmon Industry

In line with the general trends that have been seen in the salmon industry globally, the Tasmanian industry has also seen similar efficiency gains in regards to FCR and the various measures of forage fish dependency. In regards to the raw materials used, aquafeed companies have been able to take advantage of Australia's strong agricultural sector from which a range of raw materials is sourced. This has allowed the industry to reduce its reliance on imported materials such as FM and FO and include more domestically sourced products. These include plants such as lupins, canola and wheat, and of increasing importance are the by-products derived from the processing of terrestrial animals, most notably those from the poultry industry.

The industry has been involved in ongoing nutritional research through industry-based projects run by Skretting and Ridleys as well as local research institutions, most notably those from UTAS. They are also actively engaged with the key Australian national science agency, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Food Futures division in a selective breeding program. This is being carried out in conjunction with Saltas at their hatchery at Wayatinah, with the resulting progeny from the breeding program provided to the various growers for commercial production (CSIRO, 2011). Amongst the traits of interest are production-based characteristics such as growth rate, resistance to AGD and early maturation. Other consumption based traits of interest include those relating to the quality of the carcass, including omega-3 content and yield (CSIRO, 2006).

The majority of farms utilise feed management technology with the exception of some of the smaller, more traditional operations such as Petuna's Cressy hatchery. Technologies used include automatic feed distributors as well as underwater feed sensors and cameras to monitor feeding behaviour. The more recent adoption of RAS hatchery technologies by Tassal and HAC have allowed for increased control of the environmental variables such as temperature, pH, oxygen and nutrient balance that not only increases productivity, but also reduces the amount of water used (McGowan, 2010). This also occurs to a lesser extent at the sea cage operations where individual pens can be oxygenated in times of need.

Although it is recognised that these factors have helped to improve the efficiency of the Tasmanian industry there is no up-to-date calculation of the above metrics. This is not to say that the individual producers do not collect this data, but rather there is no assessment of the industry as a whole against which they can compare themselves to other industries. As such these metrics will form part of the assessment undertaken in chapter six.

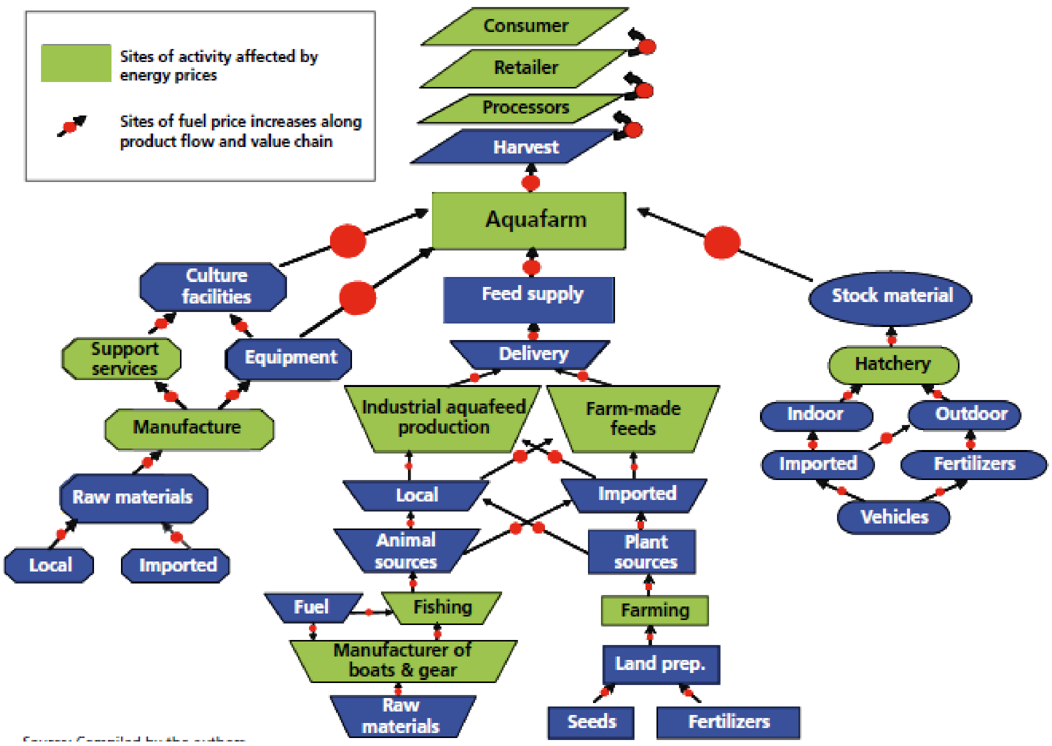
3.5 Measuring up the Metrics

Recall from chapter one that the aim of sustainability science is to better understand the individual components and complex dynamics that arise from interactions between human and environmental systems through the integration of a diverse range of disciplines (Clarke, 2007). When examining the achievements that have been made in regards to FCR and the measures of forage fish dependency it appears that the salmon aquaculture industry has already taken this approach. These efficiency gains have been achieved through the application of nutritional science to better understand the requirements of the fish and the composition of the raw materials, the adoption of engineering to develop the machines used to produce and dispense the feeds, and advancements in genetics that has allowed for the selection of the most suitable stock. Together these have allowed the industry to maximise value by adopting models that have been successful in the more established field of agribusiness (Otton and Dooley, 2010), and in doing so salmon have grown to be one of the most successful species under aquacultural production.

It was identified in chapter one that eco-efficiency involved the identification of environmental improvements that yield parallel economic benefits. To a certain extent, the above-mentioned metrics have been able to capture these goals. For example, in striving to reduce FCR as a means to achieve maximum economic returns, they have indirectly addressed the loss of nutrients and the associated eutrophication of the environment. Similarly, the search for alternative sources of nutrients and energy to minimize the risk of getting caught in the fishmeal trap has reduced their dependency on resources taken from sensitive marine ecosystems.

Despite these successes, there are three key areas in which these measures fall short of achieving eco-efficiency. The first relates to the utilization of energy. Whilst the above-mentioned metrics do a good job of accounting for the flow of nutritional energy, they completely fail to account for that which is derived from industrial sources. As identified in chapter one, industrial energy is not only the source of significant environmental damage, but it also represents one of the biggest economic costs for producers, and one that is predicted to rise considerably in the future. Just as the flow of nutritional energy was determined by the chemical composition of the raw materials used and the metabolic efficiency of the salmon to convert these into flesh, the flow of industrial energy is determined by the energy intensity of the production practices at each of the stages of the supply chain as identified in Figure 16. So in a similar way to which feed ingredients have been broken down into the individual FA and AA, it seems logical that the supply chain is broken up into smaller units to determine where efficiency gains can be achieved and future risks avoided.

Figure 16: Nodal points of impact along the product chain affected by fuel price



Source: Rana and Hasan, 2009

The second issue relates to failure of these metrics to recognise the use of by-products from other systems such as those derived from the poultry sector. Nor do they consider those associated with the value-adding of the by-products created from the salmon production process. As discussed in chapter two, these include:

- Sludge from RAS hatcheries that contains uneaten feeds and faecal matter
- Mortalities at hatcheries and salmon farms
- Processing wastes (heads, frames and viscera)

Failure to include these materials neglects the loss of nutrients, energy and the subsequent environmental damage that can occur if these are not disposed of in a responsible manner. It also misses the opportunity to highlight the benefits associated with the utilisation of these and the subsequent value that can be added to the system through the creation of additional revenue streams.

Finally, although these measures have indirectly improved some of the environmental issues associated with the production of salmon, these have been limited to those that are tied to economic gains. In reality there is often a trade-off between environmental and economic goals, and in some instances there is also a trade-off within the various measures used to assess environmental performance. For example, the replacement of FM with protein meal derived from soy reduces the burden on marine systems, but in doing so it increases the impacts on terrestrial ones such as the clearing of land and application of fertilisers that carry significant environmental costs. Similarly, the use of poultry by-products also reduces the reliance on marine inputs and can reduce costs, however these can have an impact on the subsequent nutritional value of the fish from a human consumption perspective on account of the different FA profile.

This shift from marine to terrestrial systems is likely to become more relevant in the future as demand for finite FMFOP increases. This is expected to come from a combination of continued growth in the aquaculture sector and the shift from the production of low-value omnivorous species in Asia to high-value carnivouous species that have physiological requirements for FMFOP (Rana and Hasan, 2009). At the same time that this shift is occurring, feed formulators are also using these materials in the diets of non-carnivorous species who although they do not have the same physiological requirements for FMFOP, experience more rapid and stable growth if it is present in their diets (Naylor et al., 2000).

In addition to demand from the aquaculture sector, the volume of anchoveta used for direct human consumption has risen from 10,000 tonnes in 2006 to 190,000 tonnes in 2010 (Anon, 2011). This trend is predicted to continue in the future as food security becomes more of an issue (OECD/FAO, 2011). Further to this, there has also been a steady increase in demand for human grade FO that grew from around 20,000 tonnes in 2001 to over 90,000 tonnes in 2009 (Intrafish, 2011). This growth has occurred at a time when the price of FO has been at record highs, and the global economy at an all time low, indicating that consumer demand is relatively price-inelastic. Since there is a growing awareness of the health benefits of these oils, it is predicted that demand from this sector will continue to rise to approximately 240,000 tonnes by 2013 (GOED, 2011), with a significant portion of this growth coming out of Asia (Culliney, 2011). This increase in demand coupled with supply that is expected to remain fairly stable (5.9Mt FM and 1.0Mt FO), has led to predictions that the price of FM will be up to 43% higher and FO 19% higher in 2020 compared to 2008-10 (OECD/FAO, 2011). Since this is likely to lead to an increase in the utilisation of cheaper substitute materials, there is a risk that the environmental burden of aquaculture will shift to terrestrial food production systems. Hence the need for a more comprehensive measure of efficiency to complement those discussed within this chapter.

In summary, although FCR and the various measures of forage fish dependency have been successful in helping the salmon aquaculture industry to become more efficient in the past, they are limited in their ability to continue to do so in the future. Chapter four will explore some alternative metrics that are available from the existing suite of tools in the sustainability science toolbox.

Chapter 4: Measuring Efficiency within a Sustainability Framework

Having identified the limitations of the current measures of efficiency in chapter three, this chapter will seek to find a suitable tool to provide reliable and comparable environmental data to be used to assess the eco-efficiency of production. To achieve this, what is required is a tool that allows for the flow of energy, nutrients and value through food production systems to be measured. There are a number of tools from within the sustainability science toolbox that are able to fulfill this role. A brief description of these is presented in the section below, followed by a more in depth analysis of LCA which as discussed in chapter one has been chosen as the assessment tool for this research.

4.1 Sustainability Science Tools

Since the sustainability movement took hold in the late 1980s there have been significant efforts made to develop a set of scientifically rigorous tools to measure the flows of matter and energy through the human economy (Pelletier and Tyedmers, 2011). Being a relatively new discipline, sustainability science has built on concepts from other more established areas of research, in particular economics and ecology (Bartley et al., 2007). A brief summary of the most commonly used tools can be found in Table 4. Each of these serves a related, yet functionally different purpose with majority adopting an economic approach to accounting for biophysical resources so as to measure eco-efficiency (Bartley et al., 2007).

Table 4: Brief Description of Commonly Used Sustainability Tools

Tool	Description
Cost Benefit Analysis (CBA)	Converts social and environmental costs and benefits of an activity or project into monetary terms using a variety of valuation methods
Ecological Footprint (EF)	Measures the area of biologically productive land and water area required to produce all resources that an individual or group consumes and the area required to assimilate the associated wastes
Energy Analysis	Measures the quantity of energy that flows through a defined system
Energy Return on Investment	Ratio of the energy delivered by a process to the energy used directly and indirectly in that process
Environmental Impact Assessment (EIA)	Process of identifying, predicting and evaluating the biophysical, social, and other relevant effects of development proposals prior to major decisions being made. It also deals with mitigation of impacts if the project is approved.
Environmental Input Output Analysis	Expansion of conventional Input-Output analysis (IOA) which introduces environmental dimensions into the conventional monetary analysis
Life Cycle Assessment (LCA)	Used to evaluate the resource depletion and environmental consequences of a product or activity across its entire life
Life Cycle Costing	Calculates the total costs of a product, process or an activity over its life span
Materials Flow Analysis (MFA)	Provides an overview of material inputs into and outputs of an economy by measuring the stocks and flows of specific materials
Substance Flow Analysis (SFA)	Specific type of MFA that deals with the analysis of flows of chemical substances or compounds of special interest through a defined system

Whilst none of the above-mentioned tools are able to capture the full spectrum of sustainability criteria (Jeswani et al., 2010), life cycle assessment (LCA) is widely accepted as being the most comprehensive (Hall et al., 2011; Ytrestøyl et al., 2011). LCA is a methodological framework used to quantify the environmental impacts that occur over the entire life cycle of a product or service (Rebitzer et al., 2004) by transforming anthropocentric activities into biophysically relevant metrics (Pelletier and Tyedmers, 2011). LCA originated in the 1960s as a way to assess industrial processes, with Coco-Cola being the first to adopt this framework to determine which packaging option was the least resource intensive (Baumann and Tillman, 2004). Often referred to as a cradle-to-grave analysis, LCA incorporates both upstream and downstream impacts of the production of goods and services. In doing so, it enables an assessment to be made that incorporates matters pertaining to both production and consumption (Hertwich, 2005). From a more pragmatic perspective, it provides businesses with a tool to enable them to measure and improve their environmental performance throughout their supply chain. This offers a win-win situation as it allows companies to better understand and respond to future regulatory and physical risks, as well as delivering more sustainable outcomes for society as a whole.

In comparison to majority of the other sustainability tools that focus on one particular metric such as carbon, water or energy, LCA is able to assess multiple dimensions of environmental concern using the same data set. This allows for a broader perspective to be taken that considers the trade-offs that occur between the various areas of environmental concern. This is important in ensuring that improvements made in regards to one area of environmental performance, for example carbon emissions, do not come at the cost of another such as water use. But perhaps the most important feature of LCA is that it is one of the few sustainability tools that allows for a rigorous and comprehensive analysis to be undertaken, whilst producing results that are relatively simple and easy to interpret (Bartley et al., 2007). Given that the ultimate goal of any sustainability assessment is to drive behaviour change, providing thorough results that can be understood by those who are in a position to make the necessary changes is a huge advantage. This is of particular relevance to a study such as this one where the results need to be interpreted by a range of stakeholders with varying levels of technical knowledge. This feature of LCA also lends it to multiple uses, including measuring performance over time, identifying environmental hotspots in a production process, informing product disclosure statements or comparing products and services against others (ISO, 2006a).

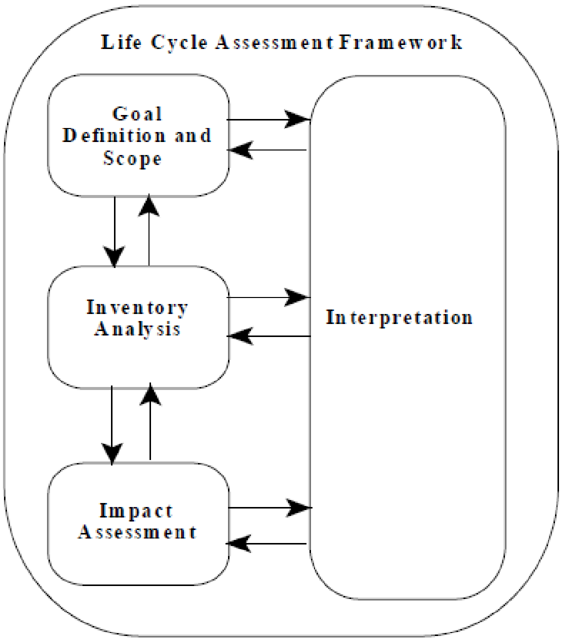
Despite the benefits outlined above, LCA is not without its limitations, the majority of which stem from the specific methodological choices made by the practitioner. Whilst many of these are of concern to LCAs in general, there are a number that relate specifically to the application of LCA to food production systems. This relates to the fact that the LCA framework was originally designed to deal with industrial processes, and was later applied to food production (Jeswami et al., 2010). As such, there have been some difficulties associated with the inherent differences that exist between industrial and food production systems. Firstly, unlike industrial systems, the movement of matter and energy through a food production system is not linear and in many cases it involves complex relationships with natural processes that require detailed modeling (Harris and Narayanaswamy, 2009a). The other major problem is that there are often multiple outputs that are inter-linked, making it difficult for the environmental burdens associated with a production system to be allocated between the various products, by-products and wastes. This issue will be discussed in more detail in 4.3.1.3 of this chapter.

These methodological challenges, together with the high volumes of data required to overcome them can make the task of modeling food production systems demanding (Salomone et al., 2011). However, due to the increasing interest from governments, industry and academia to better understand the sustainability of food systems, the LCA process is evolving to become more suitable to measuring the impact of food production (Roy et al., 2009). This includes the development of a range of guidelines and frameworks, many of which relate to LCAs in general, as well as a growing number dedicated specifically to food production systems. A selection of the most relevant to this study will be described in the following section.

4.2 LCA Guidelines and Frameworks

As the popularity of LCA grew throughout the 1990s there was a surge in opinions surrounding the best method to follow; that was accompanied by ongoing debate amongst practitioners (Jensen et al., 1997). This led to the development of a series of frameworks and guidelines to provide a more streamlined approach. The first well recognised attempt came from a group of Dutch researchers from the Institute of Environmental Sciences (CML) who developed the influential *Guide to Environmental Life Cycle Assessment* in 1992 (Heijungs et al., 1992). This was followed a year later by the Society for Environmental Toxicology and Chemistry (SETAC) who developed the *Code of Practice* (Consoli et al., 1993). These were superceded in 1997 when the International Organization for Standardization (ISO) released a set of standards as part of their existing 14000 environmental management family. In 2006 these standards were revised to their current form known as ISO14040 (ISO, 2006a) and 14044 (ISO, 2006b). The first of these sets out the underlying principles that govern LCA and identifies a clear four-step framework for practitioners to follow (Figure 17), with the accompanying ISO14044 providing more specific guidelines regarding the methodology and reporting requirements.

Figure 17: ISO Life Cycle Assessment Framework



Source: ISO, 2006a

As previously mentioned, LCA has evolved beyond its original use with industrial processes, to its current form where it is used to measure a broad range of environmental metrics for products as diverse as mobile telephones to cornflakes. To accommodate this, the ISO guidelines have had to remain flexible, and somewhat vague to allow for decisions to be made that reflect the specific needs of the unit being analysed. For this reason, these guidelines do little more than provide practitioners with a series of steps to follow rather than a clear set of procedures. In the absence of such guidance the exact method to follow continues to be a source of disagreement amongst practitioners due to the uncertainty and confusion this creates when trying to assess the validity of LCA studies (Peacock et al., 2011).

As a result, many organisations have attempted to address the lack of guidance by developing a range of supporting documentation to accompany the ISO standards. Some of the first such material came out of the joint project between SETAC and the UN Environmental Program (UNEP) known as the *Life-Cycle Initiative* that was established in 2002. The main aim of this group was to encourage the adoption of life cycle thinking in business, government and the general public through standardizing the data and methodology used by practitioners (Life Cycle Initiative, 2012). This has led to the publication of a range of guidelines such as their recent *Global Guidance Principles for Life Cycle Assessment Databases* (2011).

In Australia, the Australian Life Cycle Assessment Society (ALCAS) was established in 2001 with a similar goal to address the lack of data and clear methodology. They have set about achieving this through the development of a database and technical papers including the *Best Practice Guidelines for LCIA in Australia* (Grant and Peters, 2008) to assist practitioners working in the Australian context. Another guideline of relevance to this project is that developed by the Rural Industries Research and Development Corporation (RIRDC), which set out a framework to ensure that LCAs conducted for food and fibre systems within Australia are rigorous and comparable (Harris and Narayanaswamy, 2009b).

Such attempts have been taken one step further by a group known as The Sustainability Consortium (TSC) who formed in July 2009 as part of the ambitious plans of retailing giant Walmart to have LCAs undertaken for every product on their shelf (Bredenberg, 2011). In recognition of the lack of reliable data upon which to base these studies, they partnered with academics from Arizona State University and the

University of Arkansas as well as a number of other businesses to form the TSC. The publically disclosed goal of this group is to *"promote the use of LCA through the development of transparent methodologies, tools and strategies based on scientific principles to drive a new generation of products and supply networks that address environmental, social and economic imperatives"* (TSC, 2011). The group has since expanded to include 80 corporate members from a range of industries, with majority being multinationals such as Alcoa, Bayer, Coca-Cola, Hewlett Packard, MacDonald's, Monsanto and Unilever. To a lesser extent government and non-government organisations (NGO) also have a presence with members such as the World Wildlife Fund (WWF), the Environmental Defense Fund (EDF) and the UK governments' Department of Environment, Food and Rural Affairs (DEFRA).

Where the TSCs approach differs to other efforts made in the past is that rather than continue with a one-size fits all approach, it has separated goods into different consumer product categories and is focused on developing tools and methodologies specific to the needs of each. In doing so they are able to account for the issues that are of relevance to different products and their associated supply chains to provide a more tailored methodology. The TSC released the first round of *Category Sustainability Profiles* in November 2011 that outline the environmental impacts of relevance to ten categories of products commonly sold by their members. These are; beef, coffee, cotton towels, yoghurt, fashion dolls, laptops, laundry detergent, televisions, toilet tissues and wheat cereal. The profiles are based on comprehensive reviews of existing LCA studies, together with consultations with exerts from industry, academia and government. The group is currently researching the next round of profiles, with plans to undertake a total of 150 product categories that span across nine industry sectors. The wider benefit of this initiative is that the findings of these LCAs are being made publically available with the aim to provide a single source of data for companies to use in their sustainability assessments, and in doing so make the results obtained more comparable between studies.

Around the same time as the TSC was formed, a similar initiative known as the European Food Sustainable Consumption and Production Round Table was established. The key focus of the group echoes the goal of this research; to promote a science-based approach to sustainable production and consumption in the food sector (European Food Sustainable Consumption and Production Round Table, 2013). Their commitment to ensure that relevant information is communicated along the supply chain is reflected in the representation of the 32 members who range from farmers, processors, packaging companies, transport and consumer NGOs, along with various national government departments and international agencies such as the UNEP and FAO. To date, their major achievement has been the formulation of 10 guiding principles for the voluntary provision of environmental information to guide business-to-business and business-to-consumer communications (Peacock et al., 2011). As they currently stand, these play a similar role as the ISO standards by providing a guide to practitioners to ensure that the process of environmental assessment is rigorous and transparent, with plans to expand on this with the next phase of the project.

The above-mentioned guidelines and standards are only a small selection from the growing number that have been developed. A recent review undertaken by the global sustainability company *Pre Consultants* (2012) identified 21 such guidelines that followed a life cycle approach to assessing environmental impacts. These ranged from international standards including a number from the ISO 14000 family as well as the GHG Protocol Product Standard that has been developed by the World Resource Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). There are also a number of country specific guidelines such as the well-known PAS2050 being used to assess the carbon footprint of products in the UK. Despite the slightly different approach taken by each of these guidelines and standards, majority still use the ISO14040 and 14044 as their foundation (Pre Consultants, 2012).

It is evident from the efforts of the above-mentioned organisations that represent a diverse range of groups that there is widespread confidence in LCA as a valuable tool (Finnveden et al., 2009). This is certainly the case for the aquaculture industry who despite being relative latecomers to the LCA movement are making up for lost time with an increase in the number of studies undertaken (Hall et al., 2011). A recent literature review undertaken on LCAs in the seafood industry on behalf of the UK Seafish Authority (Parker, 2012) found that there were 46 case studies for aquaculture species that came from a total of 20 studies. Majority of these (52%) came from academic papers and to a lesser extent from industry reports and presentations. The most ambitious project to date has been the Blue Frontiers Report, co-funded by the World Fish Centre and Conservation International that was released in 2011. This used LCA to compare the natural resource requirements and environmental impacts of 13 aquaculture species across 18 countries that collectively represented 82% of global aquaculture production (Hall et al., 2011). The results of this showed significant regional variation and difference between species groups. For example, salmonids had moderate impacts in regards to eutrophication, but were high in biotic depletion as a result of their requirements for fish in the feeds. However in interpreting the findings of this report it is important to note that the authors acknowledge that the study is only a screening study based on readily available data and that the results should be viewed as a 'broad brush'.

Regardless of the species or the production system being analysed, the common finding in all aquaculture LCAs is that the feeds are the largest contributor to majority of the environmental impacts. So once again it is the feeds that are the centre of attention when it comes to sustainability. As such, studies that focus specifically on assessing the aquafeed supply chain have become popular, with the above-mentioned literature review finding an addition 22 case studies that looked specifically at aquafeeds (Parker, 2012).

Given the economic importance of the salmon industry and the ongoing debate around the sustainability of the feeds used, it is not surprising that salmon (and other salmonids) accounted for 45 percent of all aquaculture LCAs and 77 percent of the aquafeed ones in the above mentioned review by Parker (2012). These include studies that made comparisons between salmonid (trout) farming and other carnivorous aquaculture species (Aubin et al., 2009) as well as proteins derived from wild capture fisheries and terrestrial systems (Ellingsen & Aanondsen, 2006; Winther et al., 2009). Studies have also looked at the difference between technologies used on-farm (Ayer and Tyedmers, 2009), and others that have compared different feed formulations (Pelletier and Tyedmers, 2007; Papatryphon et al., 2004; Boissy et al., 2011). The most comprehensive study in regards to geographical scope has been the assessment of the global salmon industry that compared the four major producing nations of Norway, UK, Chile and Canada (Pelletier et al., 2009). Another study undertaken by the Norwegian research body Nofima looked only at the Norwegian salmon industry, with a nutritional assessment presented alongside the environmental metrics (Ytrestøyl et al., 2011).

The importance of assessing the broader environmental implications of salmon feeds has also been recognised by the Salmon Aquaculture Dialogue (SAD), a multi-party roundtable led by WWF in consultation with nine key industry stakeholders including leaders such as Marine Harvest and Skretting. This group was established in 2005 with the primary goal to develop and implement verifiable sustainability standards that minimized the negative environmental and social impacts of salmon aquaculture, whilst still allowing the industry to be economically viable (WWF, 2010). The final version of these standards was released in July 2012, with the responsibility for assessing compliance and issuing accreditation handed over the Aquaculture Stewardship Council (ASC). Criterion 4.6 of these standards states that in order to be accredited under these standards that both salmon producers and the feed manufacturers that supply them must undergo an LCA to account for GHG emissions and energy use (ASC, 2012). The associated appendices outline the details of what this assessment should include and state that either the ISO or GHG Protocol standards must be used to guide the process. Other similar initiatives such as the *Ethical Aquatic Food Index* (EAFI) that is being developed by the EU based group known as Sustaining Ethical Aquatic Trade (SEAT) are also adopting LCA. This initiative is focused specifically on tilapia, shrimp, freshwater prawns and pangasius catfish all of which are commonly traded between the developing Asian nations that produce them and the EU who consume them. The EAFI will use LCA to assess global value chains and provide a holistic, evidence-based measure of their sustainability credentials to support consumers' purchasing decisions and inform third party certifiers (CML, 2012).

Despite the growing application of LCA to aquaculture, and more specifically to the salmon industry, to date there has been no such assessment undertaken for the Tasmanian industry. In fact, at the time of writing there are no LCAs for any Australian aquaculture system or wild capture fishery. There have however been a number of recent studies for a range of other intensive animal production systems in Australia, including chicken meat (Wiedemann et al., 2012), eggs (Wiedemann and McGahan, 2011), beef and sheep, (Peters et al., 2010) and pork (Wiedemann et al., 2009). To assist in developing a rigorous study that will allow for valid comparisons to be made with LCAs for other salmon industries as well as those for other Australian agricultural commodities, a literature review of the above mentioned studies was undertaken with the results summarized in Appendix 1.

The remainder of this chapter will focus on the four stage ISO framework and identify the key factors that continue to be the source of debate amongst practitioners, with a particular focus on those that relate to aquaculture and other food production systems. This discussion will draw on a number of the guidelines and frameworks identified earlier in this chapter, along with the methods and findings from food based LCAs, in particular those included in the above-mentioned literature review. This is assist in identifying potential alternatives to the current approach to allocation and in doing so contribute to the growing body of work that is focused on improving the LCA framework for food production systems.

4.3 Overview of the ISO Framework and the Associated Methodology

4.3.1 Goal and Scope

This first step in the LCA framework is considered to be the most important as it lays the foundations for the rest of the study (Consoli et al., 1993). The goal should reflect the reason why the LCA is being undertaken as well as specify the intended application and audience so as to minimize the likelihood of the findings being misinterpreted

(ISO, 2006a). Once this has been done, the next task is to determine the scope of the study, which involves a number of steps. Whilst most of these are fairly straightforward, there are a few that are the source of dispute amongst LCA practitioners. Guinée et al. (2001) identify those that are of the most concern as being the setting of the functional unit, systems boundary and allocation. A discussion of these issues and their relevance to this study can be found below.

4.3.1.1 Functional Unit

The functional unit (FU) is the reference unit to which all other data in the study relate and the basis of equivalence when comparing product alternatives (Weidema et al., 2004). Therefore, the selection of an appropriate unit is vital in determining the purpose of the LCA as well as interpreting the findings. As the name suggests the chosen unit must reflect the function of the product or process under study which can vary from the common quantitative metrics such as kilogram or dollar value, to more obscure units that reflect qualitative characteristics such as the user's perception of the product (European Commission, 2010). Since the results can vary significantly based on the FU selected (Bassett-Mens & van der Werf, 2005; Peacock et al, 2011) the decision of which to use is highly subjective and can result in misinterpretation of the findings (Halberg et al., 2005).

The choice of FU also has a significant influence the scope of the study. For example, it is common for studies of aquaculture and other animal production systems to adopt live weight as the FU since this represents a common measure of output. However in doing so, they fail to account for the inputs required to process and transport the goods, as well as the by-products that are created in the process (Wiedemann et al., 2012). This is the case for majority of the salmon studies reviewed in Appendix 1 that used live weight, with the only exception being Winther et al. (2009) and Ytrestøyl et al. (2011) who have used a kilo of edible product. The Australian based studies chose kilogram of carcass weight (or kg of eggs), as well as a range of secondary units that are of relevance to the various stages of production; for example, live weight for chicken and pork, per piglet or weaner for pork and per hectare of land for the beef.

This study will take a similar multi-function approach by adopting tonne of carcass weight as the primary unit, which for salmon is more commonly referred to as HOG, as well as tonne of live weight and edible product so as to demonstrate the difference in the results obtained. As such, this is only a partial LCA since it does not take into consideration the downstream impacts associated with consumption and disposal of salmon that are required for a full cradle-to-grave analysis. In recognition of the importance of the feeds, a separate analysis per tonne of feed will also be undertaken to allow for the identification of the products and processes that are responsible for the associated environmental burden.

4.3.1.2 Systems Boundaries

The systems boundary defines the processes that will be included in the LCA, and in doing so also identifies those that won't (ISO, 2006a). Once again the ISO standards do not clearly state where the boundaries should be set, but rather that these should reflect the goal and scope of the individual study. The decision of what to include should also take into account is the inputs that other studies have found to be significant as well as the availability of data and resource constraints (Henriksson et al., 2011). The majority of the salmon studies reviewed in Appendix 1 used a cradle-to-farm gate approach with the only exception being Winther et al., (2009), who went a couple of steps further to include the processing and transport of the fish to the wholesaler. The studies undertaken for the Australian industries were in the middle, drawing the line at the processor gate. Although the results of these studies indicated that the inclusion of the processing stage was not overly significant to the overall LCA results, this study has chosen to include this stage since failure to do so will neglect to include the associated by-products. This would not be appropriate for this study, which is focused on making recommendations regarding alternative allocation methods. As such, a cradle-to-processor gate (downstream) approach has been taken. By taking this approach, all the upstream inputs required to produce and process the various feed ingredients will be taken into account, as well as those involved in the production and processing of the salmon itself. The upstream system is composed of a mixture of marine and terrestrial production systems from which the feed ingredients are sourced. A more detailed discussion of the inputs and outputs that will be included in this analysis will be presented in the following chapter.

Another key decision that impacts on the systems boundaries is what methodological approach to take, of which there are two choices; attributional (ALCA) and consequential (CLCA). The first of these is the more traditional approach (also known as descriptive). It aims to isolate and describe the average environmental impacts of a good or service at a particular point in time (Curran et al., 2002). This is in contrast to CLCA (or change-oriented), which attempts to predict the environmental impacts of decision or proposed change in the system under that occur as a result of market-mediated variations in production and consumption (Weidema 2003). The major difference between these relates to their systems delimitation. For ALCAs the system boundaries are based on a stoichiometric relationship between physical flows of inputs and outputs within an existing or historic supply chain (Thrane, 2006). This is in contrast to CLCAs that use marginal data to describe the consequence of decisions made in the system under investigation on supply and demand in the markets of the products identified as being substitutes (Ekvall & Weidema, 2004). It does this through the application of economic models representing relationships between demand for inputs, price elasticities and market effects of co-products (Brander et al., 2008). The difference between these approaches resembles those between partial and general equilibrium theories that have been debated in economic circles for many years, with CLCA resembling the general approach by attempting to explain market behaviour through the analysis of several interacting markets. This is in contrast to ALCA that emulates partial equilibrium models that concentrate on a single market.

Although the CLCA methodology is seen by some to provide a comprehensive and accurate indication of the environmental impacts by giving consideration to markets outside the defined systems boundaries (Ekvall & Weidema, 2004; Brander et al., 2008), there is hesitance amongst practitioners to adopt this approach due to the additional complexity associated with the use of economic models (Finnveden et al., 2009), and the associated uncertainty of predicting future circumstances (Brander et al., 2008). Others question the worth of CLCAs due to the heavy reliance on market-based information, which by its very nature is largely devoid of environmentally relevant content (Pelletier and Tyedmers, 2011).

There is acutally a third type of LCA that falls under the attributional classification but is quite different to the traditional process based approach. This is known as economic input-output LCA (EIO-LCA), which as the name suggests incorporates economic input-output analysis (IOA). IOA is an economic tool that was developed in the 1930s by Nobel prize winner Wassily Leontief as a method to trace the flow of money through a defined economy. This is done by analyzing the linkages between industries to see how the outputs from one sector are transformed to become inputs for another. The EIO-LCA method has extended this approach by taking the flows of money between sectors in an economy, or the individual businesses within a supply chain and converting these into flows of resources and emissions (Finnveden et al., 2009). This approach is seen as a way to overcome the need for complex data collection that is required for the more traditional, process-based ALCA (Cox, 2011). For this reason EIO-LCA has been the chosen methodology used by TSC for the open access LCA databases they are creating (Cox, 2011). Despite the benefits of this approach it is heavily reliant on aggregate data that looks at the average impacts of industry sectors, and is therefore more appropriate for screening LCAs that seek to identify problem areas that require further research rather than for in depth studies that aim to deliver a robust model of a complex reality (Hendrickson et al., 2006).

Since the goal of this particular study is to undertake an indepth examination of efficiency within an existing supply chain, the traditional approach to ALCA is the obvious choice. This is in line with the other studies reviewed in Appendix 1 as well as one of the seafood studies from the review undertaken by Parker (2012).

4.3.1.3 Allocation Decisions

In production systems where two or more products or waste streams are created it is necessary to allocate the overall environmental burdens of the process to each of the outputs. This is of particular importance to the salmon industry, and other intensive food production systems that are both consumers and producers of significant amounts of by-products. In their review of LCAs undertaken for seafood production systems, Ayer et al. (2007) determined that there were four separate life cycle stages in aquaculture where there was a need for allocation to take place:

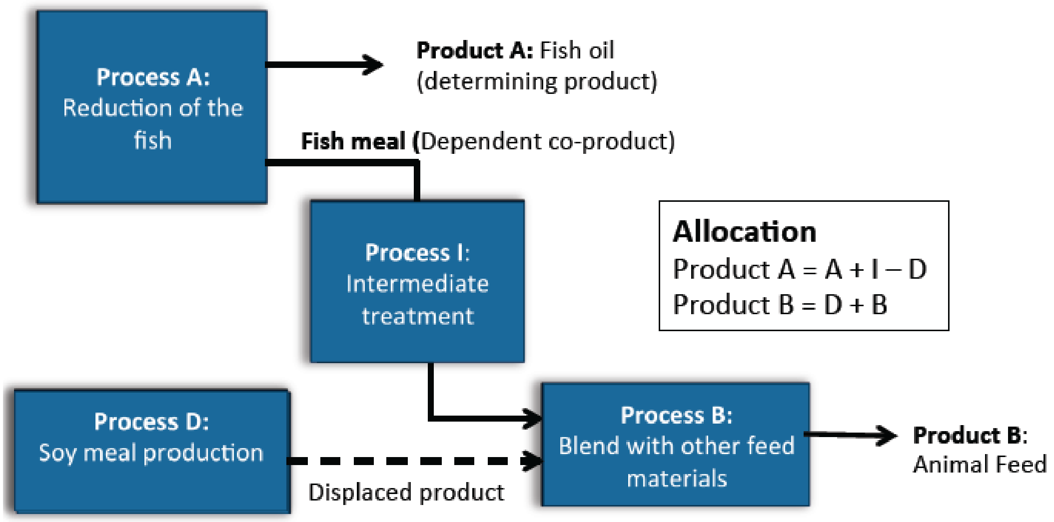
1. Landed by-catch within the context of capture fisheries;
2. The use of co-product feed ingredients in aquaculture feeds;
3. Multiple outputs from fish farms (in the case of multi-species production); and
4. The generation of by-products when seafood is processed

The ISO standards (2006b) provide a hierarchy of three allocation options, with the individual practitioner having the final decision as to which is used. Due to the significant impact this decision can have on the results, the choice of which method to use has proven to be the most controversial issues regarding the LCA methodology (Ayer et al., 2007; Pelletier and Tyedmers, 2011; Weidema, 2003; Curran, 2007; Heijungs and Guine´e, 2007; Lundie et al., 2007; Ekvall and Finnveden 2001; Guinee et al. 2001). The decision of which allocation method to use is often a reflection of individual practitioner's perspective of how the world works (Pelletier and Tyedmers, 2011), and the objective of the study. In order to determine which of these is the most appropriate for this study, each of the three allocation methods and their supporting philosophy will be discussed below, along with the associated pros and cons.

The number one preference in the ISO hierarchy is for allocation to be avoided by either dividing the multifunction process into sub-processes and collecting the data related to these, or through expanding the system boundaries (ISO, 2006b). The first of these is not often practical for food production systems and as such is less used (Ekvall and Finnveden, 2001). The systems expansion method takes quite a different approach to avoiding allocation whereby all of the environmental impacts are attributed to the product that is considered to be the primary reason why the process takes place. This is usually determined by which product represents the highest percentage of the total value of products produced. In a similar fashion to the CLCA approach, the systems expansion method views the world from a more holistic perspective whereby the availability of co-products is seen to offset the need for the production of other goods that are considered to be substitutes by the market (Weidema, 2003). Economic models are then used to determine what the marginal substitute is for the co-product, and the primary product is then credited with the environmental impacts of the avoided production of the marginal substitute (Nielsen et al., 2003).

To demonstrate this clearly, consider the example of the production of FM and FO from reduction fisheries. Since the FO fetches a higher price per unit, it is deemed to be the primary (determining) product and hence it is assigned 100% of the environmental burdens. A separate LCA for the marginal substitute for FM, which in this case would be soy meal, is then undertaken and the environmental impacts associated with the production of this are subtracted from the total for the FO. This can be seen in Figure 18.

Figure 18: Systems expansion for the production of FM and FO -



Source: Modified from Weidema (2003)

This method is preferred by the ISO and other related guidelines such as PAS2050 because it theoretically avoids the allocation issue (Lundie et al., 2007), whilst also allowing for the assessment of the indirect impacts that lie outside the systems boundaries of the product being analysed (Ekvall and Finnveden, 2001). However in practice this option is not often feasible as it does nothing more than create new allocation problems. Take the scenario described above whereby the FM was substituted for soymeal. In reality this would require a second systems expansion to deal with the soy oil that is co-produced from the milling of the soybeans. Since this method follows a parallel worldview to that associated with CLCA, it attracts similar criticisms as those identified above relating to its reliance on economic models and imperfect market data. Of particular importance are those used to select the marginal substitutes for each of the co-products as this can have a significant impact on the results of the LCA (Winther et al., 2009).

The combination of these issues has meant that despite the fact that systems expansion is number one in the ISO hierarchy, in practice it is the least popular approach (Harris and Narayanaswamy, 2009b). This is certainly evident in the seafood studies reviewed by Parker (2012) of which only ten percent used systems expansion. In regards to the salmon studies reviewed, only one adopted this approach to account for the nutrients that were contained in the sludge derived from recirculation production culture for Arctic charr (Ayer and Tydemers, 2009). Applying system expansion to this situation does not encounter the same issues as described above as there is an obvious substitute that does not create any further by-products that need to be accounted for. As such, the boundaries can be easily expanded to include the marginal substitute, which in this case was deemed to be synthetic fertilisers. Of the Australian studies reviewed, all used this same approach to offset the nutrients contained in the manures by crediting the system with the avoided impacts of synthetic fertilisers. They also used this approach to deal with the by-products obtained for the spent hens and processing wastes (offal) from the chickens, with crop derived proteins and oils selected as the marginal substitutes.

The second option under the ISO hierarchy is to partition the environmental impacts according to an underlying physical or chemical attribute that reflects the relationship between the inputs and outputs of the system under analysis (ISO, 2006b). It is common for food production LCAs to adopt this method by allocating burdens according to relative mass or energy content (Ayer et al., 2007). These are seen by many to provide a more biophysically meaningful reflection of the movement of material, energy and emissions through a production system (Pelletier et al., 2009; Pelletier and Tyedmers, 2011). They are also seen as a more reliable measure, for unlike economic values, these remain relatively stable overtime and place (Winther et al., 2009). The use of energy has become increasingly popular as many see the provision of energy to be the primary function of food production systems (Pelletier et al., 2009; Ayer at al., 2007). However, this is somewhat debatable when you consider the discussions in previous chapters that identified that the nutritional value of food is just as important as the caloric value.

The major critique of the biophysical approach is that it fails to recognize the underlying forces that drive production, and in doing so it can over-allocate the environmental burden to the lower value by-products. Take for example the offal, bones and feathers that are derived from the production of chicken meat and commonly used as a source of protein and fat in aquafeeds. The level of chicken production is determined by demand for and supply of chicken meat for human consumption. Therefore it seems logical that this product would be allocated the majority of the burden on account of the fact that if there were no demand for this product the chicken production process would not take place. However the mass of the by-products and the gross chemical energy contained within them accounts for close to 50 percent of the entire chicken (Pelletier, 2008), with the environmental burden assigned accordingly. The use of energy in particular can be problematic for some species whereby the by-products have a much higher fat content and consequently it receives a disproportionate share of the burden (Winther et al., 2009). Depending on where in the supply-chain the analysis is focused, this can be seen as either a good or a bad thing. For the producer of the chicken meat, the allocation of more burden to the by-products results in less being attributed to their product. However for the users of the by-products, in this case the salmon industry, this method can increase their environmental burden, and in doing so discourage the use of 'waste products' from production systems that have a high degree of environmental impact. This was the case in the LCA undertaken by Pelletier et al. (2009) in which the industries that used by-products from the poultry and fisheries industries had higher environmental impacts across a number of impact categories than those that used materials grown specifically for feeds. This issue is of significant relevance to the aquaculture industry, in particular salmon since it is a large user of byproducts from other marine and terrestrial systems, many of which carry a high environmental burden relative to that of crops and reduction fisheries (Pelletier, 2006).

An alternative approach is offered by the final option in the ISO hierarchy, which is to allocate based on 'other' causal relationships (ISO, 2006b), of which economic value is the most commonly used (Pelletier and Tyedmers, 2011; Finnveden et al., 2009). Proponents of this approach argue that economic value is a better reflection of the factors that determine what is produced and consumed in the market, and in doing so it avoids the situation described above whereby the by-products are allocated a large portion of the environmental burden. In accordance with this view of how the world operates, the environmental burdens are allocated based on the relative economic value, with those of higher value deemed to be the primary reason why the process took place. The difference in outcomes from this approach and that described above that uses biophysical relationships is evident by comparing the findings of the above-mentioned study to those from Papatryphon et al. (2004). In this study, four salmon feeds that contained different ingredients were compared using economic allocation to deal with the by-products included in the feeds. On account of the low economic value of these inputs the results indicated that the feeds with higher inclusion rates of by-products had a lower environmental burden. However, like all of the above-mentioned methodological choices that are based on economics this method attracts the same criticisms associated with the use of imperfect market data as previously discussed.

It is clear from the above discussion why the allocation issue remains one of the most debated topics regarding LCA as each of the methods has their own inherent pros and cons. This is evident in the inconsistency of the methods used in the seafood LCAs reviewed by Parker (2012), with mass the most prevalent (38%), followed closely by economic allocation (30%) then energy (18%). A similar pattern was found in the studies reviewed in Appendix 1 which included some studies not covered in the above analysis, with an even spread across the three methods. To assist in making the most appropriate decision for this research, recall that the overarching goal is to extend the economic approach to measuring productive efficiency within the salmon industry to also give consideration to environmental metrics. From this perspective the mass and energy options are more appropriate as they offer a better reflection of the movement of energy and matter through the system. An additional benefit to this approach is that their constancy provides a sound foundation upon which comparisons can be made over time and place. This is of significance if the results are to be used by governments and accreditation schemes such as the WWF salmon dialogue or the EAFI to assess the efficiency of different products and production systems from a range of geographical areas and that are subject to significant variations in price. This can also make it difficult for industries and the individual businesses to establish benchmarks that can be used to measure change overtime.

From a commercial perspective, if the tool is to be used to preempt future supply chain risks, this approach is far more effective in allowing those involved to measure and respond to these. To explain this concept we should return to the chicken meat example used above. Recall from chapter one that the price of energy is predicted to increase in the future, therefore if the production of chicken requires a significant amount of industrial energy, the price of the chicken meat will rise for this reason alone. Also noted in chapter one was the fact that animal proteins are relatively price elastic, meaning that the market is responsive to changes in price. There is also the impact of income elasticities. If there are substitutes (as there are) an increase in the price of chicken will result in reduced demand if there is not a counterbalancing increase in income. This will be accompanied by a decline in the availability of the associated by-products that are used as a source of the oils and meals used in aquafeeds. As dictated by the laws of supply and demand, this shrinking of supply will lead to a rise in the costs of these materials to the aquaculture industry. This is clearly an issue that would be of relevance when trying to asses future risks associated with the loss of value from the salmon supply chain.

If economic allocation were to be used, the materials derived from the chicken by-products would be assigned little to none of the environmental burdens due to the low value that is placed on these products relative to that of the chicken meat. As such, once the LCA is undertaken these will not show up as an area to be aware of in the future, despite the fact that the upstream processes required significant amounts of industrial energy. In contrast, if mass or energy is chosen as the basis of allocation, the environmental burdens assigned to these materials will provide a better indication of the relative energy requirements of the process from which they were derived, and in doing so identify hotspots in the supply chain that could potentially be an issue in the future. Therefore it is fair to say that whilst economic allocation provides an insight into the current value of products, the use of mass or energy is more likely to assist in predicting which feedstocks are likely to be subject to energy price volatility in the future. This situation is not only applicable to energy, but a number of other environmental impacts, most notably GHGs and water, all of which represent potential risks in regards to future environmental and economic costs. As discussed in chapter one, this not only affects the bottom line of companies, but also the food security of the general population through the associated increases in price and volatility in the food market. On the other hand, the decision to use biophysical allocation will have significant implications on the results for the feeds since they contain substantial amounts of by-products sourced from high impact production systems. This has the potential to lead to conclusions being drawn that a production system that utilizes materials that are otherwise not fit for human consumption is less eco-efficient than those that use materials purpose grown (or caught in the case of fisheries) for feeds that could in theory be fed to humans. Such a suggestion is illogical.

This issue of differentiating between the impacts associated with products and by-products is somewhat reminiscent of the issues associated with the early FIFO ratios as discussed in chapter three. Recall that this issue related to the over-allocation of ecological burden to species that had higher requirements for oil (e.g. salmon) or meal (e.g. shrimp). The solution to this problem was to separate the calculations used to determine the oil and meal requirements in order to give a more accurate assessment of the forage fish dependency of aquaculture species. Coincidentally, a similar approach was taken by feed formulators to improve the efficiency of their feeds by shifting the focus from the total amount of AA and FA in the diets, to one that separated these into categories based on a range of functional properties. This includes the identification of EFAs and EAAs as well as the categorization of FA based on the length and composition of their carbon chain.

In both instances described above the presentation of a total value did not allow for meaningful assessments to be made, albeit for different reasons. This research is proposing that a similar approach is applied to the allocation issue, whereby the results for the ingredients that have been purpose grown for feeds are presented separately to those related to by-products. This will allow users of the information to take advantage of the benchmarking and risk assessment benefits of the biophysical method, whilst also providing an insight into the market forces driving the availability of these materials. In other words, it will provide reliable and comparable environmental metrics to accompany economic ones when assessing the efficiency of production. Mass allocation has been chosen over gross chemical energy so as to avoid the over allocation of burden to materials that contain more nutritional energy on account of having a higher fat content. As recommended by the ISO standards, a sensitivity analysis needs to be performed in order to assess the implications that different allocation methods have on the final result, with energy, economic and systems expansion used for comparison.

4.3.2 Life Cycle Inventory (LCI)

The LCI stage involves the compilation and quantification of the relevant inputs and outputs as defined by the system boundary, and is widely regarding as being the most resource intensive part of the LCA process (Finnveden et al., 2009). It is helpful at this stage to break the system into foreground and background processes as the data required comes from different sources (EC, 2010). In this case, the foreground system refers to inputs, outputs and processes that take place in the direct production and processing of salmon (including smolt). The data required to model this should be collected directly from the source through the use of surveys, onsite observation and consultation with experts (Harris and Narayanaswamy, 2009b). The background system refers to the upstream production of the inputs that are used in the production and processing of salmon, most notably the feeds and fuels. The modeling of this is instead reliant on secondary data that is taken from existing databases and other literature sources. Over the years there has been an increase in the availability of reliable background inventory data, the majority of which are derived from studies conducted in northeast Asia, North America and western Europe (UNEP/SETAC, 2011). The largest and most widely used database is Ecoinvent, which contains inventory for over 4,000 processes that are predominantly European in origin. Whilst there is significantly less data available for the Australian context, this is changing with the growing number of practitioners contributing to the publically available Australian LCI and the Australasian LCI databases (Life Cycle Strategies, 2012). In instances where there is no data for the country or region under assessment, inventory from other countries or regions can be adjusted by changing the energy mix and adding in additional transport inputs if required (Pelletier et al., 2007).

For this study, the foreground system is comprised of the seven direct stakeholders that were identified in chapter two from whom data were collected directly via the use of formal surveys and less formal interviews. The inputs and outputs required for the fishing and farming operations that make up the background system were sourced from a range of peer-reviewed literature, government statistics and industry reports. A list of the inputs and outputs that are included in this study can be found in Appendices 2-11, along with a summary of where the data were sourced from. This was done in accordance with the ISO 14040 standards (ISO, 2006a), to ensure that the reliability and specificity of the data used is transparent. Whilst every effort was made to source data that was published within five years of this analysis, in some instances the lack of recent data made this difficult to achieve, hence older data was used.

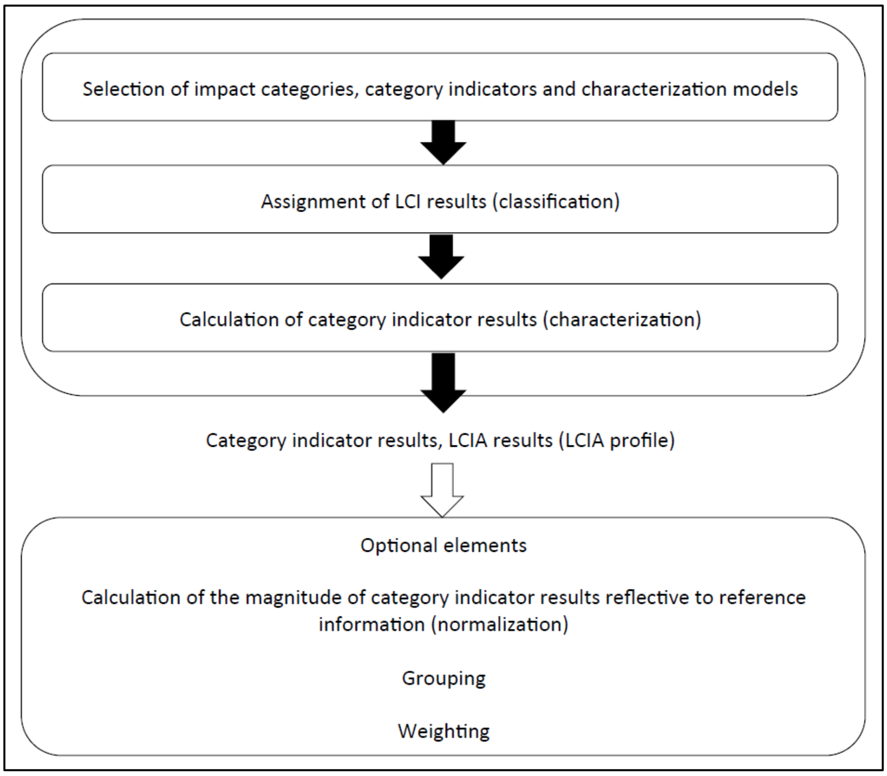
In regards to outputs, the inventory must include more than just the tangible goods and services that are produced, but also the emissions and wastes that are created in the process (Pre, 2010). Whilst some of these are incorporated into the above-mentioned databases, in some instances they need to be calculated manually by the

LCA practitioner. Based on the studies reviewed in Appendix 1, there are two major sources of emissions that occur in both the foreground and background systems. The first of these are the GHG emissions that are emitted from the on-farm application of fertilisers from the upstream production of feed inputs as well as the decomposition of organic matter and the burning of fossil fuels that occur at various stages throughout the supply chain. Most of the prior salmon LCA studies calculated these based on the emissions factors (EF) developed by the Intergovernmental Panel on Climate Change (IPCC, 2006), which were supplemented with regional data if relevant. This study bases these calculations on those prescribed by the Department of Climate Change and Energy Efficiency (DCCEE), which combines IPCC with Australian specific regional GHG models. The other emissions are those that arise from the leaching of nitrogen and phosphorus into soil and water. These were calculated using a variety of nutrient balance models, the details of which will be discussed in the following chapter.

4.3.3 Life Cycle Impact Assessment (LCIA)

The LCIA stage involves the calculation of the environmental consequences of the system under analysis by translating the LCI data into a select suite of environmental impact categories (Baumann and Tillman, 2004). According to the ISO guidelines (2006a) there are six elements required for this phase, only three of which are considered to be mandatory (Figure 19). The three optional elements are not commonly applied due to the lack of robust and agreed upon methods upon which to base the associated analysis (Harris and Narayanaswamy, 2009b). As such, only the mandatory stages of the LCIA were undertaken for this research.

Figure 19: Elements of the LCIA phase



Source: ISO, 2006a

4.3.3.1 Selection of Impact Categories

The first mandatory element is to decide on which environmental impact categories are to be included in the assessment. The ISO standards (2006a) do not prescribe a set of impact factors, but rather they stipulate that the analyst selects a set of these that best reflect the goal and scope of the LCA. Given the supply-chain focus for this study, it is important that these incorporate the environmental impacts of relevance to both the foreground and background systems identified in the previous section. To assist in identifying which categories are important to the Tasmanian salmon supply-chain, a brief review of those commonly used in aquaculture LCAs is presented. Agricultural and seafood LCAs are also reviewed since the feed ingredients are sourced from these systems.

In their analysis of agricultural LCAs, Harris and Narayanaswamy (2009) identified acidification (ACD), eutrophication (EUT), cumulative energy demand (CED), land use, pesticide use, global warming potential (GWP), abiotic resource use and ozone depletion as the most commonly selected. This was similar to the review of impact categories used for seafood production (Pelletier et al, 2007), in which GWP, ACD, EUT, CED, photochemical oxidation and aquatic ecotoxicity were identified as being the most frequently employed. The four categories that are present in both of these studies ACD, EUT, CED and GWP, were also found to be the top four in the more recent review of seafood LCAs by Parker (2012) as well as the salmon studies reviewed in Appendix 1.

In assessing the relevance of these to the Australian context, it is important to note that only two of these, CED and GWP were included in the Australian studies reviewed. In regards to ACD, this category is a measure of acid deposition that occurs as a result of atmospheric emissions of substances with a high acidification potential (Baumann and Tillman, 2004). These emissions are not produced at a large scale in Australia, and hence the extent of damage caused by this form of acidification is relatively small scale compared to other nations (EPA, 2004). Therefore despite the inclusion of ACD in studies that take place in Europe and North America, it will be excluded from this research. This is not the case with EUT, as it is not only of relevance to the Australian context, but it is essential to the goals of this research since it is a key indicator of the impacts associated with the loss of nutrients from the system.

In addition to these three, there are two other impact categories that despite being less common should be included due to their relevance to the Tasmanian salmon industry and the goals of this research. The first of these is biotic resource use (BRU), alternatively referred to as net primary production (NPP). This refers to the use of biomass produced by photosynthesis as an input to a system, which is considered to be an environmental impact in the sense that this material is no longer available to sustain ecosystem flows (Aubin et al., 2009). This relatively new category was designed specifically for the seafood sector (Papatryphon et al., 2004), and is considered to be a yardstick against which ecological demands of the various feed formulations can be measured (Pelletier et al., 2007). Given the controversy that surrounds the demands that salmon feeds place on marine ecosystems it is not surprising that 75 percent of the salmon studies reviewed for this research included this category.

The second category of relevance to this study is freshwater use. Whilst this was not common amongst the LCAs conducted for salmon or any other seafood species, it was included in all but one of the Australian agricultural LCAs reviewed in recognition of the fact that water availability is a significant issue in the Australian context. Further to this, unlike salmon production that occurs in other countries, the Tasmanian industry uses significant volumes of freshwater in the salmon production process itself on account of the unique bathing practice that is used in the treatment of AGD. As such, this study will assess water use and BRU together with the more commonly used GWP, CED and EUT. A brief summary of these can be found in Table 5.

Table 5: Description of the environmental impact categories selected for this study

Impact Category	Description	Metric
Biotic Resource Use (BRU)	Depletion of living fauna and flora	NPP (kg C)
Cumulative Energy Demand (CED)	Use of industrial energy	Gigajoules (GJ)
Eutrophication Potential (EUT)	Process whereby receiving waters become hyper-enriched by nutrients, resulting in a reduction in water quality	PO_4 equivalents (kg PO_4-e)
Global Warming Potential (GWP)	Atmospheric warming resulting from the release of a unit mass of greenhouse gas	CO_2 equivalents (kg CO_2-e)
Water Use	Measurement of the use and flows of freshwater through the system under analysis	ML

It is important to note that since the application of LCA to seafood production systems is relatively new, there are a number of environmental impacts associated with these systems that are not captured by the currently available suite of categories. These include but are not limited to the impacts aquaculture and wild capture fisheries have on biodiversity, destruction of habitat as well as other localized changes to water quality and the surrounding benthos (Pelletier et al., 2007). Whilst the research community continues to work towards developing impact categories that deal with the above-mentioned issues (Thrane, 2006; Ziegler et al., 2003;Ford et al., 2011), at the time of writing, BRU is the only one for which an agreed upon methodology has been achieved (Pelletier et al., 2007).

4.3.3.2 Classification and Characterisation

Following the selection of appropriate impact categories, the next mandatory element under the ISO framework is classification, whereby the LCI data are sorted and assigned to the impact categories to which they are known to contribute. These are then transformed into indicators that represent the size of the environmental impact for each of the selected categories through the use of equivalency factors. This process, known as characterization is the final mandatory element, and requires an understanding of the environmental mechanism that links the individual substances contained within the LCI to environmental impacts. This is done through the adoption of models that attempt to mimic the cause-and-effect chain that are based on robust, peer-reviewed protocols derived from disciplines such as environmental chemistry, toxicology and ecology (Bengtsson and Howard, 2010).

There are two different approaches that can be taken in the characterization step depending on where in this cause-effect chain the focus lies. The endpoint (damage-oriented) approach requires the model to take into consideration the entire environmental mechanism (Finnveden et al., 2009), which is terminated at the actual outcome of interest. The most common are those that relate to the health of ecosystems (e.g. biodiversity loss), human health (e.g. respiratory disease) or the depletion of a natural resource (Steen, 2001). This is in contrast to the midpoint (problem oriented) approach that is focused on an outcome that sits between the cause and effect, expressing the results in terms of their potential impact rather than their actual damage levels. For example, the contributions made to global warming are expressed as kg of CO_2 equivalents instead of the specific environmental damage .

Whilst endpoint is believed to offer more meaningful results, the additional level of modeling is generally based on a subjective assessment of the cause-effect chain, which introduces further uncertainty (Baumann and Tillman, 2004). As such this research will adopt a midpoint approach as recommended by numerous authors, including Grant and Peters (2008) in their *Best Practice Guidelines for LCIA in Australia*. This is also appropriate for the aim of this research which is interested in measuring the resource use and waste creation rather than the endpoint outcomes in terms of human and environmental health.

All stages of the LCIA can either be done manually by following an approved protocol, or through the use of a specialized LCA software package. Given the amount of data and complexity of the analysis required, it is recommended that the latter approach is used (Harris and Narayanswamy, 2009b). There are currently over 30 packages to chose from (Botero et al., 2008), with the more comprehensive being Simapro (Pre Consultants, Netherlands), GaBi (PE International, Germany), Umberto (ifu Hamburg, Germany) and Team (Ecobilan, France). Simapro has been chosen for this research as it was found to be the most commonly used package for food production LCAs (Harris and Narayanaswamy, 2009a) and seafood related ones (Parker, 2012), which was evident in the fact that all 14 studies reviewed in Appendix 1 using this package.

To further simplify and streamline the LCIA process, practitioners often adopt one of the ready-made LCIA methods that package together a predetermined set of impact categories with the associated models. There are a number of these integrated impact assessment methods available, each reflecting the environmental conditions of relevance to the technical system and regions for which they were developed (Grant and Peters, 2008). The studies reviewed in Appendix 1 used a selection of the more common methods such as Eco-indicator-99, ReCiPe and CML Baseline, all of which tend to be more European-centric. As was the case with allocation, each of these methods adopts a different approach to the principle of measurement that is based on a subjective perspective of how the world works (Baumann and Tillman, 2004). As such, there is a lack of agreement as to which method to chose. Given the temporal and geographical setting of majority of the system under analysis in this research, the 2010 version of the Australian indicator set was deemed to be the most appropriate. This was developed as part of the AusLCI database and brings together a range of methods that have been adapted to the Australian context, covering a total of nine impact categories. The details of those that are relevant for this research can be found in Table 6.

Table 6: Description of the LCIA models used for the Australian Indicator Set (2010)

Impact Category	Model Used
CED	Total energy flows based on lower heating values
EUT	Based on CML model
GWP	100 year impacts based on 2009 IPCC numbers
Water use	Addition of water used

There are two important things to note from the above table in relation to the agreed upon categories discussed earlier. The first is the absence of BRU on account of the fact that it is a relatively new category, and as such it is not currently included in any of the ready-made LCIA methods. In line with the other studies that have adopted this impact category (Appendix 1), this will be calculated manually using an agreed upon methodology that will be discussed in more detail in the following chapter. The other important thing to note is the LCIA model used to account for water. Although it is listed here as an impact category, it is really nothing more than an inventory of the total amount of water used. No attempt is made to evaluate the actual ecological outcome of this, such as desertification or depletion of aquifers, since there is a lack of agreed upon methodology to do so.

The reason for this is that the degree of environmental impact caused by water use is highly dependent on a number of localized characteristics such as the state of water availability in the area from which the water was sourced (Brown and Matlock, 2011) as well as the source of the water (Daniels et al., 2011). Given the importance of using water resources in a sustainable way, the development of suitable LCIA methods for water use continues to be the focus of research, with the Water Scarcity Index (Pfister et al., 2009) and water footprinting (Hoekstra, 2003) two of the more commonly used approaches. The ISO have also shown their commitment to developing water footprinting standards (ISO 14046) to accompany others within the 14000 series by establishing a working group in 2009 to formulate the necessary guidelines. However, due to the lack of a clearly defined methodology at the time of writing, this research will report water use as inventory data for the foreground system only. In order for meaningful conclusions to be drawn, it is not adequate to simply add the different kinds of water use to calculate a total score as this ignores the significant variation in the opportunity costs associated with the various uses of water (Hoekstra et al., 2009). In other words, water is more valuable in some applications than in others. As such, this research will classify the water use data using the indicators developed by Owens (2002) for use in LCAs. This classifies water as either *in-stream* whereby the water is used in-situ (e.g. hydroelectricity) or *off-stream* where the water is extracted from ground or surface water and diverted to another setting. This is further classified as water *use*, which refers to water that is utilized in the process under analysis, then returned to the same river basin for use by humans or other ecosystems downstream. Alternatively the water is *consumed*, whereby it's not returned for reasons such as evaporation or diversion to another river basin.

4.3.4 Interpretation

The final stage of the ISO framework is where conclusions are drawn from the results of the LCI and LCIA with respect to the goal of the study. The ISO standards (2006a) identify a number of checks that should be undertaken to ensure that the conclusions drawn are adequately supported, of which uncertainty, sensitivity and contribution analysis are considered to be the most important (Pre, 2010). Whilst the latter of these was undertaken by all of the studies reviewed in Appendix 1, a majority did not include the other two. Despite this, all three will be included in this study. Data uncertainties are addressed by applying a range of qualitative and quantitative techniques that are discussed in more detail in the following chapter. The final check is contribution analysis, which aims to identify the specific life cycle stages and materials that were a significant source of environmental burden. Not only does this allow for suitable recommendations to be made in regards to what aspects of the production process need to be improved, but it also acts as a cross-check to determine if the results obtained are consistent with what is expected based on the findings of similar studies. To do this, the system will be broken down into the major stages involved in the production process, with tables and graphs used to illustrate the relative contribution of each of these to the overall burden.

4.4 Measuring up the Metrics

Recall that the aim of this chapter was to identify how sustainability tools could be used to address the shortcomings associated with the existing measures as identified in chapter three. The first of these was the inability of the feed-related metrics to measure the efficiency of the system in regards to its utilization of industrial energy. This will be addressed by the inclusion of energy-related data to inform the LCI for the foreground and background systems, which will then be used to calculate CED as part of the LCIA.

The second shortcoming of the feed related metrics was their failure to account for the production and consumption of by-products. This will be address by presenting the results for the feed materials that are purpose grown or taken directly from wild capture fisheries separated from those that are from by-products of other production systems. This approach is intended to provide a balance between the benefits of economic and mass allocation methods. That is the results should be more consistent overtime and enable supply chain risk to be assessed, as is the case for mass allocation whilst still taking into consideration the underlying drivers of production as done by economic allocation.

The final issue that needed to be addressed from chapter three was the ability to assess the trade-offs and synergies between different outcomes. As identified earlier in this chapter, this is widely regarded as being one of the major benefits of the LCA as it allows for multiple environmental impacts to be calculated from the same dataset. As such, five relevant impact categories have been selected to allow for comparisons between the different measures of environmental performance. The impacts per tonne of the major feed ingredients will be compared to data collected on the nutritional composition and the associated economic costs of these materials. This is intended to provide environmental metrics to complement the economic and nutritional variables that are used as the basis of feed formulation.

Like the measures of efficiency discussed in the previous chapter there are a number of areas in which the LCA framework falls short of being all-encompassing. These relate to the inability of the currently available impact categories to address issues such the ecological status of the fisheries from which the reduction fish are derived, or the local impacts to the benthos and water quality at the fish farms. Whilst these matters continue to be the focus of researchers working to develop rigorous methodologies (Emanuelsson et al., 2012; Ford et al., 2012), there are other tools that are able to fill this gap. In the Tasmanian context the proximate impacts associated with the sea-cage farming are controlled by strict licensing condition that dictates a certain level of environmental health is maintained. As for the ecological health of the fisheries from which the reduction fish are taken, this is assessed by third party organisations such as the Marine Stewardship Council (MSC) or IFFO using a range of stock assessment methods. So whilst these cannot currently be assessed using the LCA method, it is fair to say that they are being addressed through other means of ongoing assessment.

4.5 A Comprehensive Measure of Productive Efficiency

Based on the discussion presented within this chapter, the LCA methodology has the potential to compliment traditional measurement of productive efficiency in food production systems to provide an assessment of eco-efficiency. However this research is suggesting that in order for the results of the LCA to provide reliable and comparable results, the environmental impacts of the feeds need to be presented separately for purpose grown materials and by-products. The remainder of this thesis will seek to determine whether the proposed modifications achieve this goal by undertaking an assessment of the Tasmanian salmon industry and its supply chain. The following chapter will provide the details of the procedures used to calculate these metrics, with a discussion of the results provided in chapter six.

Chapter 5: Life Cycle Assessment of the Tasmanian Salmon Industry

To assess the eco-efficiency of the Tasmanian salmon industry, data will be needed to model their direct operations, as well as the associated supply chain. To do this, data taken from existing databases and literature was used to model the background system, whilst the majority of the information for the foreground system was sourced directly from the seven major stakeholders identified in chapter two. Preliminary meetings were arranged with representatives from each of these companies as well as TSGA to discuss the details of the project. Following their agreement to participate, site visits were arranged to each of the major production sites including feed mills, hatcheries, marine farms and processing facilities Based on the insights gained from these visits, survey instruments (questionnaires) were devised and modified based on feedback from the individual companies before distributing them to the relevant staff members to be completed. These were specifically designed to collect detailed inventory data regarding the quantity and source of the energy, water, feed ingredients and feed used in the production process, as well as the quantity of output created in the process. A copy of these can be found in Appendix 2. The information obtained from this process was not only used to inform the LCI, but also to calculate the traditional measures of efficiency using the formulas presented in chapter three (Appendix 3).

In accordance with the guidelines set by the ISO 14040, the remainder of this chapter will provide an overview of the methodology and assumptions used for the first three steps of the ISO framework as identified in the previous chapter. The results of all the above-mentioned analyses will be presented in chapter six, accompanied by the interpretation of the findings as stipulated by the final stage of the ISO framework.

5.1 Goal Definition and Scope

5.1.1 Goal

The application of LCA to the Tasmanian salmon industry is intended to enable the research questions identified in chapter one to be answered:

1. *How can LCA be used to enhance existing efficiency metrics to provide a reliable and comparable assessment of the eco-efficiency of food production systems?*
2. *How does the Tasmanian salmon industry perform when assessed using the proposed methodology?*

More specifically it will address research objectives five and six, which are as follows:

5. *To assess if the proposed modifications achieve the desired result by applying them to an LCA of the Tasmanian salmon industry*
6. *To make recommendations as to how the Tasmanian salmon industry can improve the eco-efficiency of their operations and the associated supply chain*

5.1.2 Scope

This study will take an attributional (retrospective) approach to assess the environmental impacts associated with the production of salmon in the Tasmanian industry for the 2010-11 financial year. In addition to assessing the impacts of current production, a scenario analyses will be conducted to assess the potential impact that changes to FCR would have on the environmental performance of the industry.

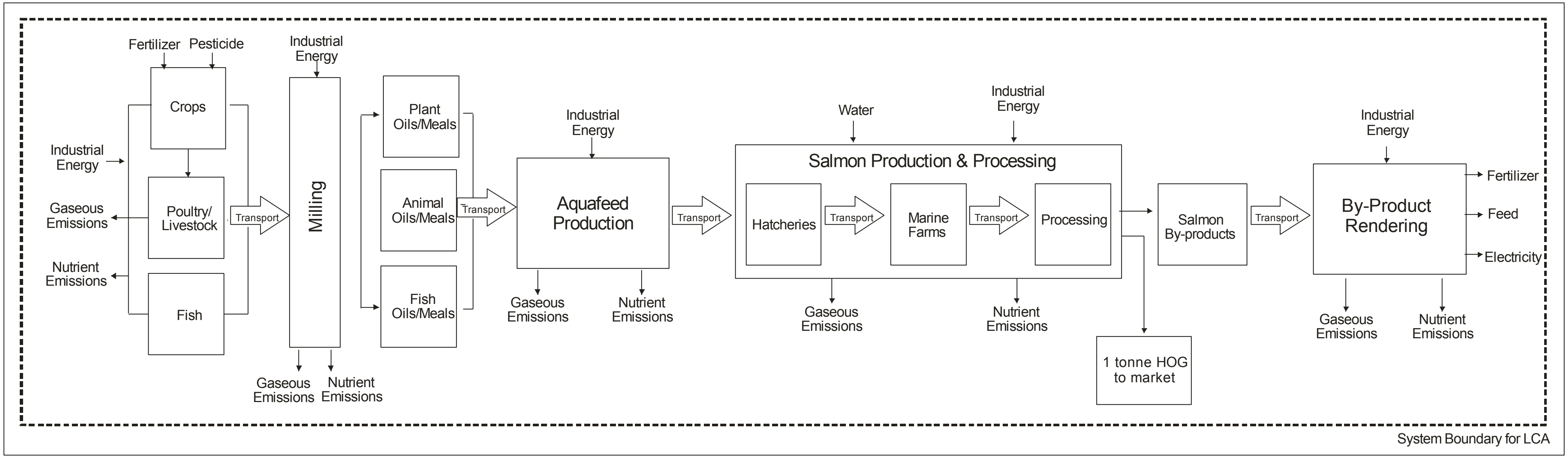
5.1.2.1 Systems Boundaries

As discussed in the previous chapter, a cradle-to-processor gate approach has been taken. The boundaries are shown in Figure 20, starting with the upstream inputs and outputs involved in the production, processing and transportation of the feed ingredients along with the milling of the aquafeeds. Next is the salmon production itself which has been separated into the three major stages as identified in chapter two; hatcheries, grow out and processing. The final phase will assess the downstream processing of the salmon by-products. Transport was limited to the movement of materials between the various stages within the identified supply chain, with no staff travel included. Other materials that were omitted are minor feed additives, cleaning agents, disinfectants and vaccines. Majority of studies reviewed in Appendix 1 did not include capital goods (infrastructure and equipment) in the foreground system, with the exception of Ayer and Tyedmers (2009). Although their results indicated that the capital goods represent between 0.06 - 10 percent of the environmental impacts of salmon production (Ayer and Tyedmers, 2009), it was decided that the large amount of data required was not justified based on the goals of this research. In regards to water use, data pertaining to the foreground system only was used since there was a lack of reliable data available for many of the background systems.

5.1.2.2 Functional Unit

The primary FU selected for this study will be one tonne of salmon HOG (equivalent to carcass weight) since this was seen to provide the best results to answer the research question. Since live weight and edible product were used in other studies, these will also be calculated to allow for more meaningful comparisons to be made. In recognition of the significant role of the feeds in determining the environmental impacts for aquaculture, these will also be presented per tonne of feed. The purpose of this is to identify which ingredients and production stages are accountable for the impacts and to enable comparisons to be made with economic and nutritional variables used in feed formulation.

Figure 21: System boundary for LCA of Tasmanian Salmon Industry



5.1.2.3 Allocation Methods

Based on the discussions in chapter four regarding allocation, the preferred method in this study will be mass. Economic, gross chemical energy and system expansion methods will also be used and sensitivity analyses undertaken to assess the degree to which the use of mass allocation impacted results. A summary of the assumptions made for all four models can be found in Appendix 4. Educated estimates were made for some of the economic allocation since there was a lack of publically available data to base this on. In regards to the system expansion model, the marginal substitutes were selected based on advice provided by representatives from the feed companies. Since no formal economic models were used, the results obtained are considered to be a rough estimate only, which was considered to be adequate for the purposes of this research since it was not the primary allocation method.

5.1.3 Data Quality and Uncertainty Analysis

All models are by definition a simplification of the real world, and are therefore imperfect due to natural variability in the system under analysis as well as the underlying assumptions made by the researcher. Whilst any divergence between reality and the modeled outcomes cannot be completely avoided, it can be minimized through applying checks and balances to identify major discrepancies. This research adopted a qualitative approach whereby the data collected and the subsequent analyses were discussed with stakeholders and experts in the field to identify problems and viable explanations. This is more problematic for the background system since it relies on secondary sources and models that can lack in temporal, geographic and product specificity. Unfortunately this was unavoidable since there was no better alternative, so instead, these instances have been documented in this chapter and the associated appendices to ensure that they are taken into consideration when interpreting the findings.

5.2 Life Cycle Inventory (LCI)

The following section will elaborate on the major assumptions made for the LCI phase as well as highlight any limitations and the potential implications these might have on the findings of the analysis.

5.2.1 Foreground System

The majority of the data used to model the foreground system was collected directly from the five salmon producers via the above-mentioned questionnaires (Appendix 2). As noted in chapter two, some of the producers also grow a small percentage of Ocean Trout *(Oncorhynchus mykiss)*. These have been included in the analysis as it was difficult for the producers to separate the inputs and outputs required for each species. This was not seen to be material since this species comprise under five percent of total fish production, and the nutritional guidelines used to formulate their feeds are very similar to Atlantic salmon (FAO, 2013). As such the results will be presented per tonne of salmon with no differentiation made between the two species. A production-weighted average was constructed using the data provided by the feed and salmon companies, a summary of which can be found in Appendix 5.

Detailed data on logistics was also collected for the transportation of inputs and outputs that were identified by the stakeholders as being significant. This included the movement of feeds from the suppliers to the various production sites, smolt from the hatcheries to marine farms and the HOG from slaughter to processing. Since contractors undertake the majority of this transportation, it was not possible to obtain fuel usage data, so instead tonne kilometers (tkm) was used as a proxy. This required the producers to provide information on the average load as well as the pick-up and drop-off point for each of the major transportation routes so that distances could be calculated using whereis.com (Telstra Corporation Ltd., 2011). Fuel efficiency is also affected by truck type, whether or not the truck is empty for the backhaul and the breakdown of rural versus urban driving. The latter is important due to the fact that stopping, starting and idling are more common in urban driving which increases fuel use. For all interstate transport a breakdown of 80% rural, 20% urban was used, with no backhaul for the company included, as it was assumed that they would pick up another load for a different customer for the return journey. For smaller internal trips within Tasmania (e.g. for smolt), the truck is empty on the return journey and a 50% rural, 50% urban breakdown was used to reflect the driving conditions (P. Houle, pers. comm., August, 2012).

The Tasmanian electricity mix varies from year to year based on the availability of water to power their hydroelectricity system. Any shortfall is provided by a combination of gas, wind and the Basslink, an underwater cable that connects the island state to the mainland energy grid. To model this in Simapro, the energy mix for the 2010-11 period was sourced from Transend Networks Pty Ltd (2011), which was taken to be representative of a typical year. The inventories for the production and distribution of the diesel, petrol and LPG that was used on-site at the various facilities was taken from the Australasian LCI database in Simapro. In regards to the GHG emissions generated from their utilization, this was calculated manually using the Department of Climate Change and Energy Efficiency (DCCEE) Emissions Factors (2012a). Landfill gases were included in the analysis, however they since they accounted for less than one percent of the total they will not be reported.

5.2.1.1 Hatcheries

The hatchery operations require clean and well-oxygenated water as well as energy to control the temperature and lighting, and in some cases the on-site generation of oxygen. Volumes of water and energy required for these processes were collected from each of the four companies that operated hatcheries. The data required to calculate the nutrient losses to the surrounding environment was calculated using the mass balance model outlined by Buschmann et al., (2007). This looks at the inputs (g) of nitrogen and phosphorus contained within the feeds and multiplies these by the digestibility (%) to obtain the total amount of nutrient digested by the fish (g). Both the nutrient content and digestibility were taken directly from the nutritional data provided by the two feed companies. The difference between the amount digested and the total nutrient in the feed is then assumed to be lost as particulate to the surrounding environment. To account for the loss of dissolved nutrients, a reference value for carcass composition for nitrogen and phosphorus is used, then adjusted to account for the FCR to obtain a value for the percentage of nutrient contained in a tonne of feed that is converted to body mass. This is then subtracted from the total amount digested to obtain an estimate of the amount of soluble (dissolved) nutrient that is lost. A summary of the assumptions made and the source of the data used can be found in Appendix 6. Although these models were designed to estimate emissions from sea cage operations, it is assumed that the estimates provided will be sufficient for the purposes of this research.

In the case of the RAS hatchery systems, not all of the nutrients accounted for above are released directly into the environment. Instead, the particulates are removed during the water treatment process and are then sent to agricultural properties where it is used as a soil conditioner. In the studies reviewed in the previous chapter, the removal and utilization of these wastes as fertilisers was accounted for in the assessments of pig, chicken meat and egg production systems, as well as one of the salmon studies (Ayer and Tyedmers, 2009). In all four instances, systems expansion was used whereby it was assumed that the nutrients would offset the need for the production of synthetic fertilisers. Whilst for the terrestrial animal systems this was significant due to the relatively high volumes of waste, in the case of the salmon example this contributed less than one percent to the overall total. As such it was deemed to be insignificant and not included in this analysis.

In contrast to the more efficient RAS hatcheries, the flow through systems rely on settling ponds to collect the waste materials before returning the water to the original water source. In the absence of any water quality data or sludge composition, the nutrient balance model alone was used to model emissions from these facilities. Despite the fact that the ponds would generate GHG emissions as a result of the denitrification process, a lack of data made it difficult to account for this, hence these were omitted from the study. Therefore the emissions to air for this part of the production process are conservative whilst the losses to water are likely to be over estimated. Since the feeds used in the freshwater phase of production represent only 3 percent of the total feeds, the exclusion of this from the inventory was not deemed to be significant.

In regards to water use, only the RAS hatcheries were able to provide data on the volume of water used since majority of the flow through systems did not have any processes in place to record this data. According to the classifications of water use described in the previous chapter, this would fall under the *in-stream use* category since the water is merely diverted from its natural course and returned to the same place in much the same condition as it was extracted, with some minor losses along the way. As such, although the omission of this data from the analysis will mean that results obtained will underestimate the real volumes used, in terms of environmental damage, the in-stream use classification is of the least concern (Owens, 2002), therefore this was not deemed to be a major limitation.

5.2.1.2 Marine Farms

The marine farms require energy to power machinery, boats and generators that are used to provide the artificial lighting to control the growth of the fish and to oxygenate the water as required. Data on this was collected directly from the companies, along with the volumes of water used for the freshwater bathing. The same nutrient balance model described above was used to estimate the loss of nitrogen and phosphorus to the environment as a result of the uneaten feeds and the associated metabolic by-products. The input of smolt per tonne of live weight salmon was based on the average smolt weight of 130g with each tonne containing 222 fish at an average weight of 4.5kg (F. Ewing, pers comm, August, 2012). The volume of mortalities collected from the sea cages was recorded and treated as a by-product of salmon production, with the environmental burdens assigned according to mass with the only exception of the 300 tonnes from the west coast production that went to landfill.

5.2.1.3 Processing

The processing stage requires energy to run the refrigerators, freezers, ice machines and processing equipment, as well as water for the cleaning of the plant. There are two distinct phases involved in this stage of production, the first of which involves the gutting and cleaning of the whole fish to create HOG. The majority of these are sent in this form to markets where they are sold as fresh fish. The remainder undergoes a second process where by it is value-added to create products such as smoked salmon, frozen fillets, pates and canned goods. To allow for comparisons to be made with other food production systems and to avoid the need to allocate amongst the various goods, this study will only include the gutting phase.

To assess the impacts per tonne of HOG, the loss of blood, eggs and guts was calculated, it was estimated that these by-products accounted for two, five and ten percent respectively of the live weight of salmon (P. Bennet, pers. comm., March, 2012). As was the case with the mortalities, the environmental burdens were allocated to these according to their relative mass. Since one of the processing facilities conducts both gutting and value-adding processes at the same location it was difficult to determine the water and energy requirements for the gutting and cleaning separately. As such an average from the facilities that deal only with the first of these processes was used and adjusted to reflect the production volumes from the excluded plant.

There are two sources of nutrient emissions that arise from the processing of salmon. The first is the blood water from the slaughtering of fish, and the other from the processing plants that gut, fillet and value add the fish. For plants that had trade waste agreements with local water treatment facilities, the volumes of wastewater sent to these were entered into Simapro as wastewater with an Australian specific process used that calculates the associated emissions to water and air, as well as the energy required to undertake the process. This was modified to reflect the specific energy mix of Tasmania relative to that of the mainland states.

Other plants used settling ponds to deal with the wastewater whereby the water is left to rest for a period of time to remove some of the pollutants and then discharged into nearby waterways or used for irrigation. For those that discharged into water bodies, the threshold amounts set by the Tasmanian EPA were used to estimate the emissions of nitrogen and phosphorus to the surrounding environment. As was the case with the settling ponds at the hatcheries, lack of data made it difficult to account for the emissions to air that would occur as a result of denitrification process and were therefore omitted from the study.

5.2.2 Background System

5.2.2.1 Feed Production

The transformation of raw materials into feed pellets requires energy to power a number of processes. This includes the mechanical grain handling and mixing of the ingredients, the production of steam that is required for the conditioning and extrusion of the materials, as well as for the drying and vacuum processes used to ensure the uniform absorption of fats. In addition to energy, water is also required by the boiler to produce steam, with smaller amounts needed for general cleaning and maintenance of the mill. The total energy and water usage for each of the feed mills was collected directly from the two feed companies via formal surveys and informal discussions. Since both companies produced feeds other than those used by the salmon industry, the energy and water were allocated according to the percentage of total production (by weight) that were made for the Tasmanian salmon industry.

As previously noted in chapter three, salmon are fed a range of specifically formulated diets throughout their life with the aim of meeting specific physiological needs and to create desirable organoleptic properties. To simplify these diets for the purpose of this LCA, the nutritionists at each of the feed companies constructed two production-weighted feeds to represent the average formulations used at the freshwater and saltwater phase of the production process. Although these were modeled separately for the analysis, given the high degree of commercial sensitivity, a production weighted average of all feeds used by Tasmanian industry in the 2010-11 FY has been calculated and presented in Appendix 7.

Logistics data relating to the distance, load, mode of transport and their place of origin for all the raw materials used in the feeds was also collected, with the same method as described above for the foreground system. In addition to road transport, a number of materials sourced from within Australia used rail, with the distances taken from the Australian Railway Association (2004) in conjunction with whereis.com (Telstra Corporation Ltd., 2011). For products sourced from overseas, no consideration was given to the transport required to get the raw material from the producer or processor in the country of origin to the nearest port due to the inherent uncertainty in the assumptions required. Instead only the sea distance between the port of origin and the Australian port identified were accounted for, with the distances calculated using Sea.Rates.com distance calculator (2011). As such, the estimates provided can be considered to be an underestimate.

Approximately nine percent of the feeds used in 2010-11 were imported from Europe. Of the 7,080 tonnes that were imported, nine percent was sourced from Skretting's European factories to cover the shortfall that occurred as a result of the renovations being done to their Tasmanian plant during this time. As such the volume of imported feeds was higher than an average year. The remaining feeds came from Biomar (90%) and Aller Aqua (1%) which were sourced directly from these companies by the salmon producers. Given the importance of the feeds to the overall impacts, and the significant difference in the feed materials used in the European feeds compared to those made in Australia, it was deemed appropriate to model these separately. To do this, the authors of the global LCA (Pelletier et al., 2009) were contacted in regards to the data they used to model the European feeds in their study. They kindly agreed to provide a Simapro process file that represented the average European feed for 2007, with the details of the materials used and the inclusion rates detailed in the supporting documentation to their study. Although this data was slightly out of date it was deemed to be representative of the feeds used by the Tasmanian industry since it was based on data collected directly from European mills owned by Skretting and Biomar.

The distance from port of origin to the final destination was calculated using the same methodology as noted above.

As previously stated, it is common in LCAs that assess aquaculture and other intensively grown animals that the raw materials used to produce the feeds carry the highest environmental burden of the entire production process. Therefore it is necessary that a detailed inventory is collected for the upstream inputs and outputs involved in the production and processing of these ingredients. As can be seen from the production-weighted average in Appendix 7, a range of raw materials from both terrestrial and marine systems sources are used in the Tasmanian feeds. The inventory data required to model these production systems came from a range of existing databases, literature sources and advice from experts, the details of which will be discussed in the following sections.

5.2.2.2 Crops

Studies of cropping systems show that the major inputs responsible for the environmental burden are fertilisers (in particular urea), and to a lesser extent the pesticides and fuels used in the on-farm machinery (Brock et al., 2012; Biswas et al., 2008; Narayanaswamy et al., 2004). Therefore in order to model the production systems for the crops used in the salmon feeds as well as those for poultry, data on the above-mentioned inputs and subsequent outputs (yield) were sourced from gross margin budgets published by the Department of Primary Industries (DPI) in the states from which the crops were sourced (Appendix 8). In cases where more than one gross margin budget was available for a particular state, DPI staff were contacted to advise which zones accounted for majority of production and the relevant budget selected. A production-weighted average of these was then calculated to determine the final inventory which is presented in Appendix 9, including the assumptions made regarding transportation. All Australian crops were assumed to be no-till since this land management practice is undertaken on majority (75%) of Australian land under cropping (ABS, 2011). In all instances 100 percent of the burden was assigned to the portion of the crop that is used for food/feed, with a zero value assigned to all other biomass such as stalks and leaves.

Fertilisers are responsible for a significant portion of the environmental impacts due to the emissions to air, soil and water that occur when they are applied to the soil. Of particular relevance to this study are their contributions to the eutrophication and global warming potential impact categories. The first of these relates to the loss of nitrogen and phosphorus to local water bodies since these are two of the key nutrients responsible for eutrophication. To account for nitrogen losses, this study used the mass balance approach described by Brentrup et al., (2000) whereby the inputs and outputs of nitrogen from the system are estimated, with the difference between the two used to calculate the loss. This was accompanied by a similar model by Dalgaard et al. (2008) that was used to account for phosphorus, with the nitrogen and phosphorus content of the crops taken from Preston (2004). It should be noted that the accuracy of these models is limited by the fact that there is no regional data available to account for the differences in the climatic conditions, soil properties and farm management practices that are responsible for significant variations in emissions (Brentrup et al., 2000). Therefore, this was based on the broad assumption that the majority of grain and oilseed production in Australia takes place in the grain belt of Australia which has predominantly sandy-loam to clay-loam soils (CSIRO, 2006c) with an average rainfall of 500mm per annum (BOM, 2011).

There are two major sources of emissions to air, those that are nitrogen based, and those that are carbon based. The first of these occurs when the fertilisers are applied to the soil, at which time the nitrogen compounds contained within the fertilisers become part of the local nitrogen cycle. As such they are subject to the naturally occurring processes of volatilization, denitrification and nitrification that release nitrous dioxide (N_2O), ammonia (NH_3), nitrous oxide (NO), and inert dinitrogen (N_2) into the atmosphere (International Fertiliser Industry Association and FAO, 2001). In regards to the influence of these gases on the impact categories selected for this study, N_2O is the most significant as it is a potent GHG. To a lesser extent NH_3 and NO also contribute to GWP through the redepostition of these substances on the soil, which provide a substrate from which more N_2O emissions can be made (IPCC, 2006).

To calculate the amount of nitrogen that is lost as N_2O via the direct and indirect processes described above, emissions factors (EF) are used to calculate the percentage of the raw material input that is converted into the resulting emission. The EFs used for this study were taken from the National Inventory Reporting (NIR) Guidelines (DCCEE, 2012b) which use a combination of Tier 1 default values from the Intergovernmental Panel on Climate Change (IPCC) methodologies (2006) as well as Tier 2 values that have been calculated specifically for Australia, a summary of which can be found in (Appendix 10). Similar to the comments made above regarding the limitations associated with using generic nutrient balance models, the EFs also do not take into consideration regional variation, in particular the Tier 1 values that are based on European studies (Brock et al., 2012). However, in the absence of more specific information, these were deemed to be sufficient for the purposes of this research.

The indirect emissions associated with leaching and run-off were not included as the NIR guidelines (DCCEE, 2012b) state that this only occurs in regions where the evapotranspiration is less than precipitation. This is measured by the evapotranspiration to precipitation ratio (Et/P), with a value <0.8 indicating that leaching is possible. Given that majority of cropping in Australia takes place in dryland conditions with an Et/P ratio >0.8, emissions from leaching and runoff were not considered in this study.

The other factor that is of relevance to GHG calculations is the interaction that crop production has with the balance of organic soil carbon. This refers to the carbon contained within the plant residues, living roots, biological organisms and decomposed material within the soil, which can act as both a sink and a source of carbon dioxide. In the absence of tested methodologies to accurately account for the movement of carbon through the soil in agricultural systems, this has not been included despite the significant impact it could potentially have on the results. This is because accurate results would have also been difficult to obtain given the high degree of uncertainty as to which regions the crop inputs used in the feeds were grown.

Some of the crop inputs required processing before they reached the feed mill. These were modeled using crop specific data where available, and in instances where it was not, inventory for a similar crop was used and modified accordingly. Whilst most of the inventory data available provided representative estimates of energy use from which GHG emissions could be calculated, the nutrient losses incurred in the processing were not well documented. As such, the values for the eutrophication are underestimated, although this is not expected to be of any significance to the overall results.

A summary of the data sources that were used as the basis of the LCI for crops and the assumptions made can be found in Appendix 8, along with the yield data presented in Appendix 4 that was used to determine the allocation for these production systems. In addition to the crop-based inputs obtained domestically, a number of processed crops were imported. Both the primary production and processing phases for these materials were modeled using existing data from a range of sources, the details of which can also be found in Appendix 8. The electricity required for the processing of these materials was based on the country specific energy mix as reported by the International Energy Agency (IEA) (2011b), with the Simapro process modified to reflect this.

5.2.2.3 Poultry Inputs

The salmon feeds used in the Tasmanian industry contain protein meals and oils that are derived from the rendering of offal, bones and feather from the poultry industry. These are predominantly sourced from the broiler supply chain with insignificant amounts coming from the egg industry (B. Hopkins, pers. comm., August, 2011). As such, a recent LCA of Australian broiler production by Wiedemann et al. (2012) was used to model the upstream inputs associated with the by-products used in the salmon feeds. This study focused specifically on broiler production that occurred in two Australian states, Queensland and South Australia, with the major difference between these identified as being grain inputs used in the feeds. In Queensland the primary grain used was sorghum (43%) with a smaller portion of wheat (21%). This is in contrast to the South Australian feeds that had wheat as the primary grain (46%) with barley contributing a further 14 percent. The reason for this variation is explained by the fact that feed producers tend to favour materials that are grown in close proximity to their mills so as to minimize the associated transportation costs (ACMF, 2011). This explains the variation in feed inputs since sorghum is the main grain crop grown in Queensland, whereas wheat is in South Australia wheat, with barley coming a close second (ABARES, 2011).

The poultry inputs used in the salmon feeds are sourced from five Australian states including Queensland and South Australia, as well as Victoria, New South Wales and Western Australia. The inventory for the three states that were not included in the above-mentioned study were all based on the South Australian data on account of the grain production that occurs in these states. This was determined from data contained in the Australian Bureau of Agricultural and Resource Economics and Science (ABARES) annual crop report (2011), a summary of which can be found in Table 7. Although NSW also grew a significant portion of sorghum, this was overridden by the fact that wheat represents a greater portion of total grain production in the state. The only other difference might be the inclusion of lupins in the Western Australian diet (ACMF, 2011), however this was not deemed to be significant as only a small portion of the poultry inputs were sourced from this state.

Table 7: Australian grain production by state (2010-11)

State	Wheat (tonnes)	Barley (tonnes)	Sorghum (tonnes)
NSW	10,600	2,500	751
Vic	4,089	2,450	0
Qld	1,305	159	1,469
WA	4,700	1,300	0
SA	5,600	2,900	0

Source: ABARES, 2011

The values for the yield of the chicken meat and the various by-products used in the Australian study varied significantly from those reported in the LCA for global salmon undertaken by Pelletier et al. (2009). To ascertain the validity of this, industry averages of yield were obtained from Australian Chicken Meat Federation (ACMF) (V. Kite pers. comm., March, 2012). When compared to the other two studies the results obtained were similar to those of Pelletier et al. (2009), therefore these were used in the allocation process (Appendix 4). Data regarding the yield of meals and oils from the offal and the feathers were based on advice provided by experts from the milling industry (B. Hopkins, pers. comm., March, 2012). The electricity and water data for the milling of the chicken by-products was taken from an industry survey undertaken by the Australian Rendering Association (ARA) for the 2010-11 period (2011). State specific energy mixes were used to account for differences in the power sources, generation technologies and distribution infrastructure used.

The inventory provided by Wiedemann et al. (2012) that was used to model the poultry system for this study included the emissions of nitrous oxide and methane from the storage and application of chicken manure. This was calculated using the IPCC (2006) and DCCEE (2010) methods, of which the latter was used for this study. Since it is common practice for the litter and manure to be used as fertilizer (ACMF, 2011), the chicken production system was credited with the avoided burdens of the production of the equivalent amount of synthetic fertilizer production. In addition to the GHGs resulting from the manure, there are also nutrient (nitrogen and phosphorus) emissions to water and soil. However, these were accidentally excluded and not incorporated into the model. Unfortunately this was unable to be corrected as when it was discovered the license to the Simapro software had expired. To estimate the extent to which this is underestimated, a rough calculation was made manually using the formula used as the basis of the CML model (Heijungs et al., 1992) which suggests that the results per tonne of poultry inputs would be approximately double what are reported here if these nutrient emissions had been taken into account. As such, the results obtained for eutrophication are an underestimate of the true value and should be interpreted with care. The inventory used to model this supply chain can be found in Appendix 11.

5.2.2.4 Mammalian Inputs

Meat meal and blood meal from mammalian rendering are also used in the salmon feed formulations. In reality these products would contain a mixture of cattle from dairy and beef production, as well as sheep and swine (ARA, 2012). However for the purposes of this research it was deemed satisfactory to model this system based on beef cattle production to simplify what would otherwise require a large amount of inventory data that is outside the scope of this study. The reason beef cattle were chosen was because cattle represented majority (71%) of total mammalian meat produced in 2010-11 (ABS, 2012a), with cattle raised specifically for beef accounting for 91 percent of this (ABS, 2012b). In taking this approach it is realized that the results are likely to overestimate the environmental impacts of the blood and meat meals due the higher environmental impacts cattle have in comparison to pigs. However this was deemed to be insignificant since pork represented only 11 percent of total Australian meat production.

Beef cattle production takes place throughout Australia. It is an extremely diverse industry, with the breed, production method and environmental conditions varying from farm to farm (ABS, 2005). Majority of cattle spend their lives in an open range grass fed environment, with approximately 34 percent transferring to feedlots for fattening for a few months before slaughter (MLA, 2012). Three LCA studies have been conducted for Australian cattle production (Peters et al., 2009; Eady et al., 2011; Ridoutt, Sanguansri & Harper, 2011), of which the Ridoutt, Sanguansri & Harper (2011) study was selected since it covered a broad range of production methods (pasture and feedlot finishing), products (yearling through to heavy steers) and environments (high-rainfall coastal country to semi-arid inland country). As such it was seen to be more representative of the diversity within the Australian beef industry than the other two studies. Despite the variation in the production systems, the range of results for the six systems was not so large, with the lowest result 10.1kg CO_2-e/kg liveweight for and the highest being 12.7kg. The inventory used for this study was therefore based on a mean of these two, using a nominal enterprise unit of 100 cows over a one year time period. A summary of this inventory can be found in Appendix 12.

The Australian FarmGAS tool (Australian Farm Institute, 2012) was then used to calculate the biogenic emissions created from enteric fermentation, manure and urine, as well as emissions from soil and fertilizer used for pasture. This is a tool developed by the Australian Farm Institute based on the Department of Climate Change and Energy Efficiency (DCCEE) accounting method. The inventory data from the above-mentioned inventory was used to model the system, with default values provided by the FarmGAS toll used for all unknown variables. A simplified feedlot ration was modeled using the grains presented above in Table 7, with the proportion based on the relative production volumes. In the absence of national data on fodder crops, grass silage was from the Ecoinvent database. For the grass fed system it was assumed that all manure and urine was returned to the pasture. For feedlots the manure production rate and nutrient composition were calculated using the mass balance (Watts et al., 2011), using the assumption that nitrogen makes up 2.6 percent of the body mass of beef cattle and .69% is phosphorus (Koelsh & Lesoing, 1999). The relative yield of meat, blood and meal were taken from MLA Eco-efficiency handbook (2002). The electricity for the milling of the by-products was taken from an industry survey undertaken by the Australian Rendering Association (ARA) for the 2010-11 period (2011). State specific energy mixes were used to account for differences in the power sources, generation technologies and distribution infrastructure used. A summary of the all this data can be found in Appendix 12.

5.2.2.5 Fisheries Inputs

Previous studies undertaken for wild-capture fisheries indicate that the production and use of fuels accounts for majority of the associated impacts (Thrane, 2004; Hospido and Tyedmers, 2005). As such, this was the only data collected to inform the LCI for this stage of the supply chain. The most dominant factors affecting fuel use in fisheries were identified by Tyedmers and Parker (2012) as being the species targeted, the location in which the fishing activity takes place and the gears being used. As such, this data was collected for the three fisheries inputs used in the Tasmanian salmon feeds; anchoveta, albacore tuna and skipjack tuna. The details of these will be discussed in the following paragraphs, with the detailed inventory and sources of data provided in Appendix 13.

The anchoveta are sourced from the South American industry, which as discussed in chapter three, is a dedicated reduction fishery that is dominated by industrial boats that predominantly use purse seine nets. High catch rates make this fishery one of the most efficient in regards to energy use and the associated emissions to air and water (Freon et al., 2010). Unlike anchoveta that are caught specifically for the purpose of reduction, the tuna products used in the salmon feeds came from the rendering of the by-products of the canning industries in Thailand and Samoa. There are significant differences in the species caught and gears used in these two countries which influences the amount of fuel used.

Thailand is home to the largest tuna canning industry in the world, with majority (92% by weight) of the fish caught in the Western Central Pacific Ocean (WPCO) (FFA, 2008). Approximately 72% of tuna caught from the Pacific Ocean are Skipjack, 76% of which are caught with purse seine gears (Miyake et al., 2010). In contrast, the Samoan tuna canning industry is based on albacore tuna (82%) (SPC, 2010) which is a much larger species with white flesh that earns a premium on the American market where majority of the finished product is exported. Longline fishing is the gear of choice for the commercial fisheries in Samoa (SPC, 2010), which is less fuel-efficient that purse seine gears. These assumptions were used to determine the fuel use in these two fisheries, which was taken from Tyedmers and Parker (2012). These values were assumed to include the fuel required to freeze the fish on-board, with no consideration given to the refrigerant gases. A limitation of this study is that by-catch is not taken into account; therefore all fuel is attributed to the target species.

The processing of the fish and the milling of the by-products also requires energy. These values, as well as the yields of the various products were taken from a range of literature sources, the details of which can be found in Appendix 13. The electricity mix in the country where the processing took place was based on the country specific information from the IEA data (2011b), with the Simapro process modified accordingly.

5.2.3 Processing of Salmon By-Products

The process used by Seafish to convert the salmon waste into oils, meals and soil conditioners is reliant on energy to fuel the boilers to cook the biomass and to power the driers that turn the wet product into a fine power meal. This data was collected using a formal questionnaire, along with the quantities of the various outputs that are created as a result of this process. Water quality data was sourced from a report undertaken by Cardno (2010) and used to model the nutrient emissions to soil and water. To assess the nutritional gains associated with the utilisation of these materials, data on the nutritional composition of the products was estimated from secondary sources, with the assumptions listed in Appendix 14.

5.3 Impact Assessment

Recall from chapter four that the impact categories being assessed for this research are GWP, EUT, CED, BRU and water use. The first three of these were calculated using the 2010 Australian Indicator Set, with Simapro software as the platform from which this was done. As noted earlier in Table 6, this indicator set measures GWP using IPCC (2009) numbers for 100 year impacts, EUT using CML model (1992) with no localization and CED is the total energy flows based on lower heating values. Water use was calculated only for the foreground system due to the lack of data available for many of the feed ingredients. The volumes of water are expressed using the categories proposed by Owens (2002).

In the absence of a computer-aided calculation for BRU, impacts for this were calculated manually. To do so, the approach taken by Papatryphon (2004) was followed whereby net primary productivity (NPP) is used as a proxy for biotic resource use. This is based on thermodynamic principles that are the basis of all biological systems, and measures the rate at which plants in an ecosystem incorporate atmospheric carbon through photosynthesis. For the crops used in the feeds, the calculation of NPP is based on the carbon content of the portion of the crop that is utilized. This was calculated based on the macronutrient composition of the dry matter (DM) of the raw materials, which was taken from the nutritional information provided by the feed suppliers. These were then converted to carbon using conversion factors from Rouwenhorst et al. (1991) where the carbon content is based on the nutritional composition of the food, and expressed as a percentage of DM where carbon content is 53% for protein, 44% for carbohydrates and 80% for lipids. This same approach was also used to calculate the NPP for the chicken feeds, with the energy transfer losses accounted for by multiplying the BRU for the feeds by the FCR for chicken. This was based on an average of 1.87 from the Queensland (1.89) and South Australian (1.85) supply-chains analysed by Wiedemann et al. (2012).

For fisheries, the calculation is based on the formula developed by Pauly and Christensen (1995). The formula was founded on the second law of thermodynamics, which states that as energy is transferred some of it is lost as waste heat. The authors estimate based on a large set of ecosystem model results that in wild systems 10 percent of energy contained in biomass of prey is converted to biomass in the predator, with the other 90% lost in the transfer. As such, the higher the trophic level of the fish, the greater the amount of energy lost. This is the basis of their calculation as shown in Equation 10 that estimates the grams of carbon that must be fixed by autoptrophs in order to yield a set amount of the species of interest (Tyedmers, 2000). In line with the other studies that have included BRU as an impact category, this calculation was used, with the trophic levels of the various species sourced from Fishbase (2010). A summary of these can be found in Appendix 15.

$$P = (M/9) \times 10(T-1)$$

Where:

P = the mass in carbon appropriated (in kg) where 9 represents a 9:1 conversion ratio from wet weight to carbon content, or conversely carbon is 11 percent of wet weight

M = mass of fish required (wet weight)

T = trophic level of the organism

Equation 10

5.4 Interpretation

Having detailed the assumptions made and the source of data used to model the foreground and background systems that make up the Tasmanian salmon industry in this chapter, the following one will present the results. This will include the interpretation of the findings, which will complete the final stage of the ISO framework. To assist in making recommendations, a scenario analysis will also be presented to show the extent to which improvements in FCR will help to improve the eco-efficiency of the Tasmanian salmon industry in the future. This was done by modifying the amount of feed used to model the production of one tonne of salmon as well as the associated nutrient emissions on farm using the calculations in Appendix 6. This approach is somewhat limited in that it assumes that the feeds are made of the same blend of ingredients, which in reality is unlikely to be the case. As such, these findings are to be seen as a rough estimate only.

In regards to the methodology used to estimate the ratio of by-products to purpose-grown feed materials, this considered only the inputs required for the primary production stage since the processing and transportation would be required regardless. The feed ingredients were separated into those that were derived from each of the above-mentioned categories and the associated impacts assigned to these. For the crop by-products, gluten from the processing of wheat for starch and corn for sugar syrup were included. Although some would argue that soy oil should also by-products, these were not included since they have a range of other applications in human and animal feeds. Regardless of the debate that this decision could potentially evoke, it is not expected to have a significant implication on the results obtained since soy oil was only included in two out of the five feeds analysed, in which it contributed less than three percent to the total impact of the feeds.

To make an assessment of the implications that utilizing the by-products from the processing of salmon, the nutritional composition of these materials was estimated using the assumptions presented in Appendix 14.

Chapter 6: A Comprehensive Assessment of Efficiency in the Tasmanian Salmon Industry

This chapter will begin by presenting the results of the traditional measures of productive efficiency that were described in chapter three. Following this, the findings from the LCA will be discussed and in doing so complete the forth step of the ISO 14040 framework. First the results per tonne of HOG will be presented so as to identify where in the supply chain these impacts are incurred and the specific activities that are responsible. Following this, the implications of key methodological choices on the results will be reviewed by comparing different functional units and allocation methods. Based on these findings, comparisons will be made with LCAs for other salmon production systems, as well as other popular Australian proteins (chicken, pig, eggs) in an attempt to benchmark the environmental performance of the Tasmanian salmon industry. The final section will present the results of the LCA to formulate the recommendations and conclusions presented in chapter seven.

6.1 Traditional Measures of Productive Efficiency

In the 2010-11 financial year, the Tasmanian salmon industry produced 52,891 tonnes of biomass, with just three percent (1,834 tonnes) coming from the freshwater hatcheries and the remainder from the marine farms. During this time a total of 41,237 tonnes of biomass was harvested for sale. The majority was sold as HOG (72%) or further value added to become fillets (16%), smoked salmon (12%) and other small goods (0.3%), with a total market value of $AUD 437.7 million. This was produced using a total of 75,000 tonnes of feeds of which 15 percent (11,230t) was imported from Europe. This is above the amount that would usually be imported since it includes the 4,297t of saltwater feeds imported by Skretting to cover the shortfall associated with their expansion during this time. The remainder came from local production, with Skretting accounting for 41 percent and Ridleys 44 percent. This gave the industry an overall eFCR of 1.4, which was above the global average of 1.3 (Tacon and Metian, 2008).

The feeds were comprised of a range of imported materials (48%) as well as those sourced locally (52%). As can be seen in Figure 21, these were a combination of crop-based inputs (28%), those from fisheries (34%) as well as meals and oils derived from poultry (30%) and mammalian (8%) production systems. The other important thing to note is the inclusion of by-products compared to materials that are purpose grown/caught for animal feeds. According to the summary presented in Table 8, 48 percent of the materials used in the Tasmanian feeds are by-products. This includes all of the poultry and mammalian inputs mentioned above, as well as a smaller amount of fisheries and crop by-products.

Figure 21: Source of Feed Ingredients in Tasmanian Salmon Feeds

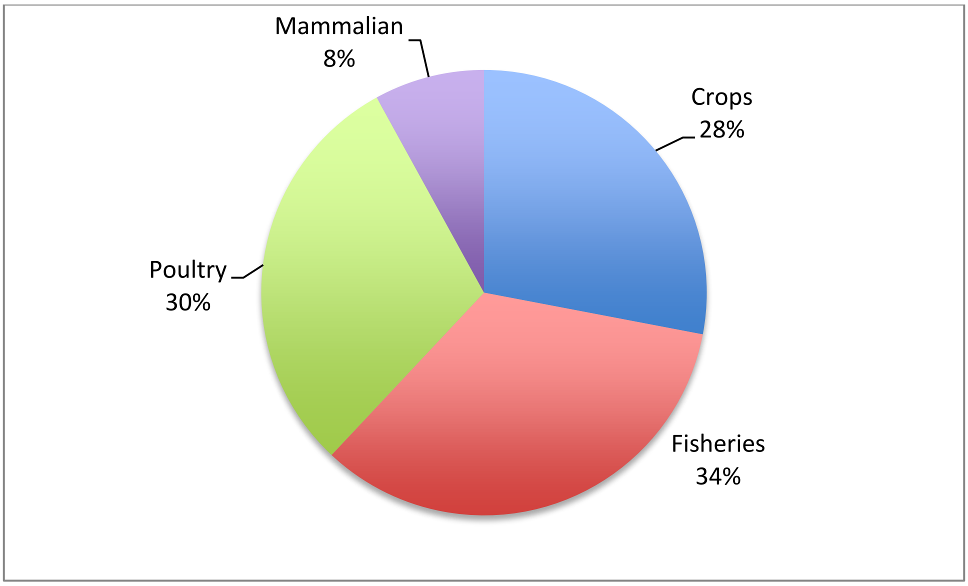
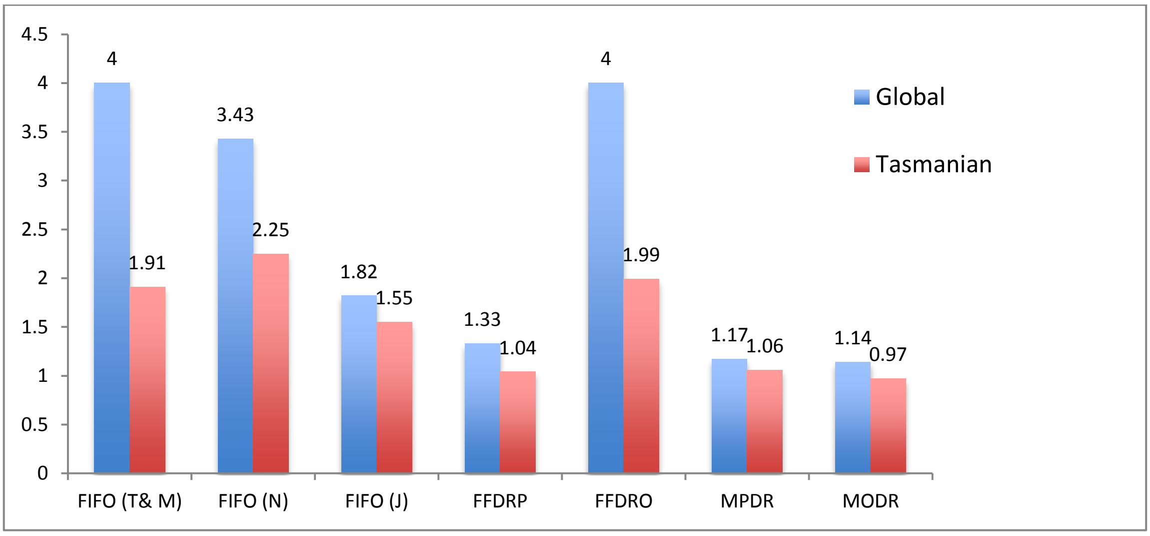


Table 8: Breakdown of purpose grown materials and by-products used in feeds

Source of Materials	%
Crop	26
Reduction fishery	26
Total Purpose Grown	***52***
Crop by-products	2
Fisheries by-product	8
Poultry by-product	30
Mammalian by-product	8
Total by-products	***48***

The high levels of terrestrial materials combined with the use of fisheries by-products has meant that despite having a higher than average FCR, the Tasmanian industry is below the global average for all seven of the measures of forage fish dependency discussed in chapter three. This can be seen in Figure 22, which compares the global averages calculated in chapter three to those calculated for the Tasmanian industry using the raw data provided by the salmon farmers and feed producers. A summary of the values used as the basis of these calculations can be found in Appendix 3.

Figure 22: Comparison of Tasmanian and Global Averages for Measures of Forage Fish Dependency



T&M = formula used in Tacon and Metian, 2008; N = formula used in Naylor et al., 2009; J = formula used in Jackson, 2009

Whilst it is clear from the metrics presented in Figure 22 that the Tasmanian industry is performing well compared to other salmon industries in regards to limiting its use of marine resources, the following section will interpret the findings of the LCA to see how the industry performs against environmental metrics.

6.2 Interpretation of LCA Results

6.2.1 Cumulative Energy Demand

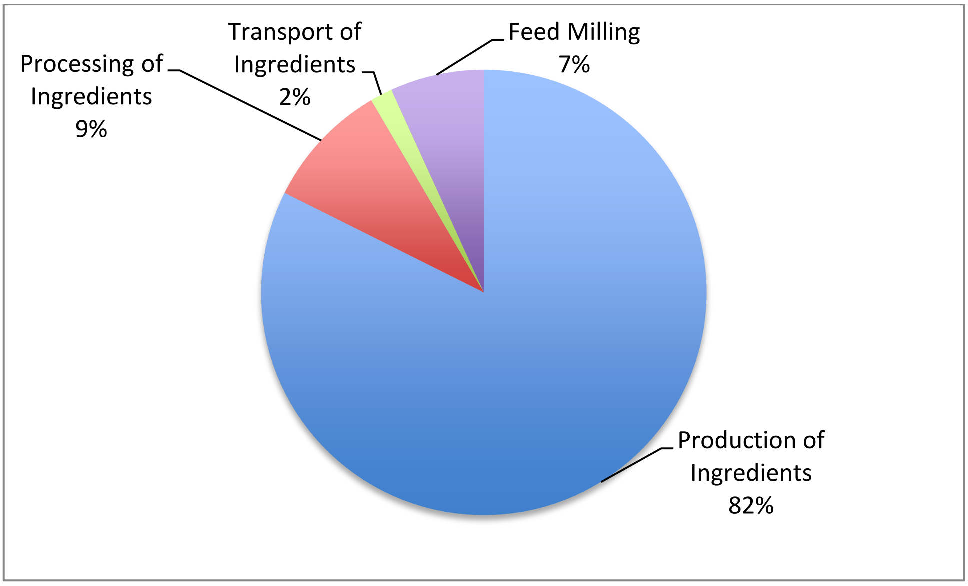
The results for CED presented in Table 9 show that a total of 67,700 MJ of energy was used in the production of one tonne of HOG. Majority of this (83%) came from the upstream production of the feeds, followed by marine farming at 13 percent. Of the portion attributable to the marine farms, 48 percent was used in the transportation of feeds with an additional one percent for the transport of smolt, and the remainder from the liquid fuels (43%) and electricity (8%) used on-site. For the processing and hatchery stages, over 50 percent of energy used was for electricity to operate the facilities, with smaller amounts for transportation. Although it would have been interesting to compare the energy requirements of the RAS hatcheries to those that were flow through, this could not be done as the data provided by the companies was in aggregated form.

Table 9: Results for CED at the various stages of production

Stage of Production	CED (MJ)	% total
Hatcheries	1,680	2%
Marine ops	8,740	13%
Processing	900	1%
Feeds	56,400	83%
Total	**67,700**	

Of the 56,400MJ attributable to the feeds, 92 percent came from those that were sourced from Australian feed suppliers, of which the majority (82%) relates to the upstream production of the raw materials (Figure 23).

Figure 23: Contribution analysis of CED for Australian feed production



To determine which of the materials was responsible for the impacts incurred in the primary production phase, results for each of the feed ingredients used in the Australian made feeds were calculated and summarised in Table 10. It is important to note when looking at the values in this table that they relate to one tonne of feed not per tonne of HOG as this would require 1.4 tonnes of feed. From this analysis it can be seen that a significant portion of the total impacts stem from the meal that is made from the albacore tuna by-products, which despite being only seven percent of the feed by weight account for 28 percent of the total CED. This is due to the fact that this fishery is very fuel inefficient, requiring more than three times the amount of fuel per tonne as for skipjack tuna and 60 times that used per tonne of anchoveta (Appendix 13).

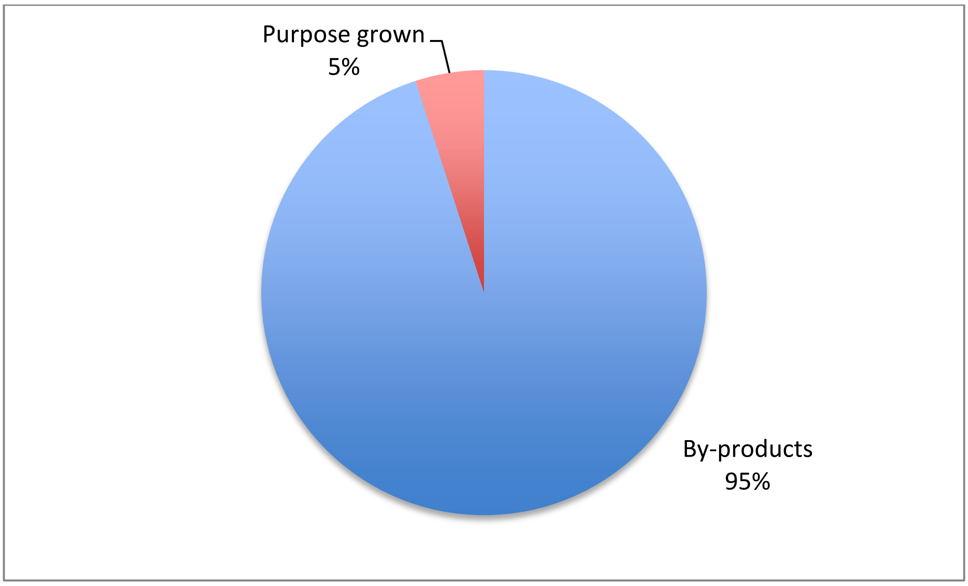
The other significant contributors were the poultry and mammalian inputs that respectively accounted for 30 and 8 percent of the feed by weight, which was again disproportionate to the 49 and 17 percent of the overall impacts. This is in contrast to the crops that represent just two percent of the impacts and 29 percent of the feed. The reason for this stark difference is a combination of the additional impacts incurred in the production and distribution of the feeds, the inefficiency of feed conversion (FCR 1.87 for chicken and 12.5 for cow) and the low yield of the oils and meals relative to the associated raw material.

Table 10: CED for primary production phase for feed ingredients used in the Australian made feeds (per tonne feed)

Feed Ingredient	*Inclusion Rate (%)*	MJ	% of impact/t feed
Crops	***28***	***807***	***2***
Wheat	6	173	0.5
Dehulled lupins	5	133	0.4
Faba bean	9	254	0.7
Wheat gluten meal	2	66	0.2
Soya Protein Concentrate	6	181	0.5
Fisheries	***34***	***11,900***	***32***
Anchoveta meal	18	592	1.6
Anchoveta oil	8	255	0.7
Albacore Tuna by-product meal	7	10,600	28.1
Skipjack Tuna by-product meal	1	442	1.2
Poultry	***30***	***18,200***	***49***
Feather meal	6	3,620	9.6
Poultry meal	9	5,630	14.9
Poultry oil	15	8,960	23.7
Mammalian	***8***	***6,500***	***17***
Blood meal	5	4,440	11.8
Meat meal	3	2,060	5.5
		37,700	

When the data are presented separately for the materials that are by-products and those that are purpose grown (Figure 24), the results indicate that majority (95%) of the total 37,700MJ embodied in the one tonne of feed is attributable to production processes that are driven by demand for other foods. The implications of this from a sustainability perspective will be discussed in more detail at the end of the chapter.

Figure 24: Contribution of purpose grown materials and by-products to total CED for the primary production stage of feeds



6.2.2 Global Warming Potential

The production of one tonne of HOG resulted in the emissions of 9,320kg CO_2-e (Table 11), with the feeds once again the major source (92%) of impact. The higher contribution of feeds to GWP compared to CED can be explained by the non-energy related emissions of methane and to lesser extent nitrous oxide that are produced in the production of the agricultural inputs. This relationship will be described in more detail when the contribution of the individual feed ingredients is discussed below.

Table 11: Results for GWP at the various stages of production

Stage of Production	GWP (kg CO2-eq)	% total
Hatcheries	58	1%
Marine farms	506	5%
Processing	40	0%
Feeds	8720	92%
Total	**9,320**	

In this instance, the Australian feeds accounted for an even higher percentage (96%) of the feed-related impacts, with the primary production of the raw materials responsible for majority (91%) of these (Figure 25). The reason for this is the inclusion of terrestrial animal proteins in the Australian feeds, in particular those of mammalian origins. For as shown in Table 12, although these represent just eight percent of the feed by weight, they accounted for 60 percent of the overall GWP. This was due to the biogenic methane emissions created from the microbial breakdown of carbohydrates during the digestion process. Similarly, the poultry ingredients were also responsible for a relatively high portion of the burden (26%) due to the direct emissions from the manure at the shed as well as those that arise in the process of growing the crops used for the feeds.

Figure 25: Contribution analysis GWP for Australian feed production

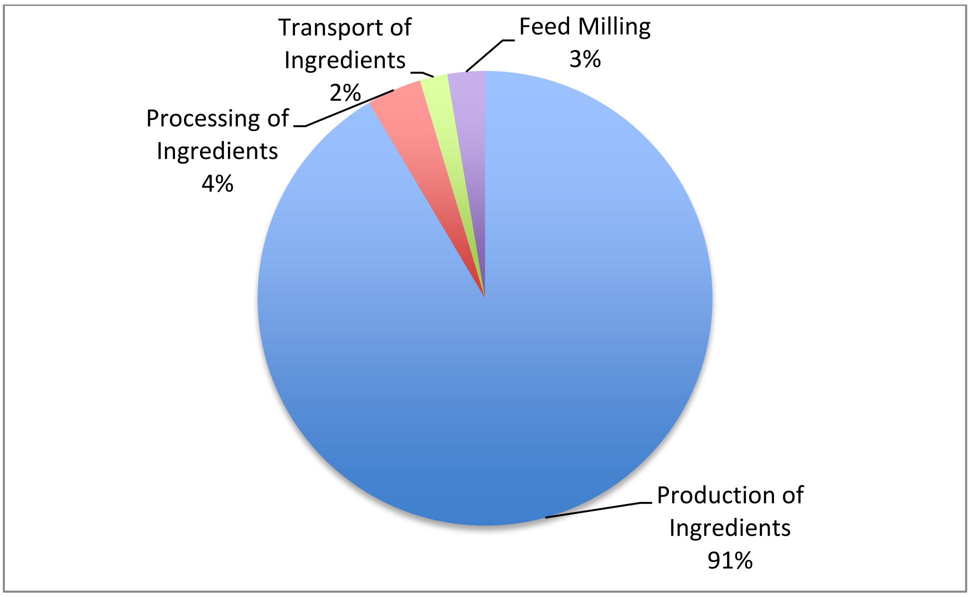
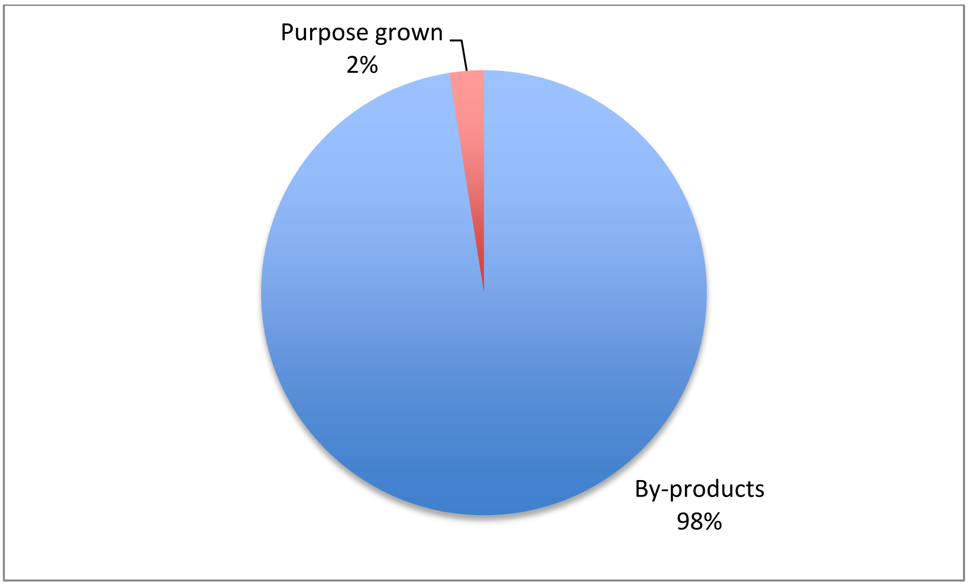


Table 12: GWP for primary production phase for feed ingredients used in the Australian made feeds (per tonne feed)

Feed Ingredient	*Inclusion Rate (%)*	kg CO_2-e	% of impact/t feed
Crops	***28***	***111***	***2***
Wheat	6	19	0.3
Dehulled lupins	5	17	0.3
Faba bean	9	32	0.5
Wheat gluten meal	2	5	0.1
Soya Protein Concentrate	6	38	0.6
Fisheries	***34***	***826***	***12***
Anchoveta meal	18	41	0.6
Anchoveta oil	8	18	0.3
Albacore Tuna by-product meal	7	736	11
Skipjack Tuna by-product meal	1	31	0.5
Poultry	***30***	***1,690***	***26***
Feather meal	6	350	5.3
Poultry meal	9	473	7.1
Poultry oil	15	867	13.1
Mammalian	***8***	***9,390***	***60***
Blood meal	5	2,740	41.3
Meat meal	3	6,640	19.1
		6,640	

The other significant contributor to the GWP was the albacore tuna meal (11%), which is directly related to the high fuel inputs as described earlier. Based on these results, it is not surprisingly that when the results were split between ingredients that are by-products and those that are purpose grown, almost all (98%) were attributable to by-products (Figure 26).

Figure 26: Contribution of purpose grown materials and by-products to total GWP for the primary production stage of feeds



6.2.3 Eutrophication

Unlike the previous categories, the marine operations were the major contributor (83%) to eutrophication (Table 13). This was caused by the nitrogen and phosphorus released to the aquatic environment from the uneaten feeds and metabolic by-products from the digestive process. Majority of the remaining impacts (16%) were attributable to the production of the feeds. As can be seen in Table 14, mammalian ingredients were again the major source of emissions (66%) due to the significant amounts of nutrients contained in the manure. For the same reason, the poultry by-products were the second largest contributor (26%), although as previously discussed this is an underestimate due to the failure to fully incorporate the nutrient emissions from the manure in the model of the chicken supply chain.

Table 13: Results for EUT at the various stages of production

Stage of Production	EUT (kg PO_4-e)	% total
Hatcheries	0.73	1%
Marine ops	59.4	83%
Processing	0.10	0.1%
Feeds	11.8	16%
Total	**72**	

In interpreting these findings it is important to note that the EUT for many of the feed materials is likely to be underestimated due to a number of reasons. Firstly the models used to estimate the emissions created in the primary production stage were based on a number of assumptions and data taken from secondary sources. Secondly, the inventory data related to the processing of the raw materials was for energy use only, with no mention of emissions of nitrogen and phosphorus.

Table 14: EUT for primary production phase for feed ingredients used in the Australian made feeds (per tonne feed)

Feed Ingredient	Inclusion Rate (%)	kg PO_4-e	% of impact/t feed
Crops	***28***	***0.5***	**6.0**
Wheat	6	0.02	0.2
Dehulled lupins	5	0.04	0.5
Faba bean	9	0.26	3.3
Wheat gluten meal	2	0.03	0.4
Soya Protein Concentrate	6	0.13	1.6
Fisheries	***34***	***0.1***	**2.0**
Anchoveta meal	18	0.02	0.3
Anchoveta oil	8	0.01	0.1
Albacore Tuna by-product meal	7	0.08	1.0
Skipjack Tuna by-product meal	1	0.01	0.1
Poultry	***30***	***2.07***	**26**
Feather meal	6	0.45	5.7
Poultry meal	9	0.68	8.6
Poultry oil	15	0.94	12
Mammalian	***8***	***5.28***	**66**
Blood meal	5	3.65	46
Meat meal	3	1.63	21
		7.95	

6.2.4 Biotic Resource Use

Since BRU is determined solely by the raw materials used to make the feeds, it is not surprising that none of the total 63.7t C/t HOG was incurred in the foreground system. When looking at the contribution of the individual feed materials (Table 15), the fisheries products are the most significant contributors, in particular the albacore tuna. Once again it is not an industrial input that is to blame for this, but rather the trophic level of the species since BRU is basically a measure of where in the food chain a particular organism sits. As such, the carnivorous tuna species have a much higher BRU than smaller pelagic fish such as anchoveta that sit further down the food chain. They are also significantly higher than the mammalian and poultry inputs since their diets are predominantly crop-based.

Table 15: BRU for primary production phase for feed ingredients used in the Australian made feeds (per tonne feed)

Feed Ingredient	*Inclusion Rate (%)*	t C	% of impact/t feed
Crops	***28***	***0.14***	***0.3***
Wheat	6	0.03	0.06
Dehulled lupins	5	0.03	0.06
Faba bean	9	0.05	0.11
Wheat gluten meal	2	0.01	0.02
Soya Protein Concentrate	6	0.02	0.05
Fisheries	***34***	***42***	***93***
Anchoveta meal	18	3.29	7.28
Anchoveta oil	8	2.76	6.11
Albacore Tuna by-product meal	7	33.6	74.3
Skipjack Tuna by-product meal	1	2.50	5.53
Poultry	***30***	***1.2***	***2.6***
Feather meal	6	0.16	0.35
Poulty meal	9	0.29	0.64
Poultry oil	15	0.72	1.59

Mammalian	***8***	***1.7***	***4***
Blood meal	5	1.05	2.32
Meat meal	3	0.66	1.46
		45.2	

6.2.5 Water Use

In the process of producing one tonne of HOG, a total of 66KL water was utilised by the activities undertaken in the foreground system (Table 16). This was sourced from a combination of reticulated supply (2%), bores (5%), rivers or dams (93%). According to the classifications of water use outlined in Owens (2002), 90 percent of this was off-stream use, all of which was attributable to the freshwater bathing process that takes place at the marine farming stage of production. Of the remaining 10 percent that was classed as off-stream consumption, majority (71%) was used at the hatchery stage, with a smaller portion used for processing (39%). Since the values presented for the hatchery phase of production are for the RAS hatcheries only, the total water utilisation is an underestimate of reality. However the omission of this was not deemed to be significant in allowing for the sustainability of the system to be assessed. The reason for this is that water used in the flow through systems that were not accounted for is classified as in-stream water use, and the activities at the hatchery do not have a significant impact on the quality of the water. As discussed in chapter four, this is deemed to be sustainable as it does not affect the ability of downstream users from utilising these water resources for other anthropocentric or for ecological services.

Table 16: Classification and source of water used per tonne

	Volume Used (KL)	Volume Consumed (KL)
Hatcheries		4.82
Marine Farms	59.3	
Processing		1.91
TOTAL	**59.3**	**6.73**

As previously noted, the assessment as to whether or not water use is considered to be sustainable can only be done if the localised conditions are taken into consideration. In regards to the Tasmanian salmon industry, majority of the water utilised is for the freshwater bathing process. This is taken from either purpose built dams that are located close to the marine farms, or to a much lesser extent directly from rivers. Given the close proximity of the marine farms to the estuary there are not many other users that are affected by this extraction, with the exception of the water that is lost to evaporation from the dams. Once the water is used to bathe the fish, it is returned to the same river catchment with very minimal change to the water quality. As such, it is reasonable to assume that this practice does not have significant implications for other water users with the exception of the portion that is loss through evaporation from the dams. In saying this, it should be noted that the East coast of Tasmania where this activity takes place is prone to seasonal drought (Hundloe, 2012), therefore in times when water flow is low the extraction of water for bathing purposes could impact the ecology of the lower estuary. Of the remaining 6.73KL that is used for the hatchery and processing stages, 80 percent is taken from nearby bores or rivers, with extraction rates determined by the Tasmanian EPA. Once used, this water is then sent to settling ponds before being used to irrigate nearby fields and orchards. Without a more detailed assessment of the impacts of these activities on the water supply, meaningful conclusions are unable to be drawn.

6.3 Implications of key Methodological Choices

6.3.1 Comparison of Allocation Methods

To test the sensitivity of the results to the allocation method, the model used for this LCA was rerun for three other allocation methods using the assumptions listed in Appendix 4. The results of this are presented in Table 17. Water use has been excluded from this analysis since it only includes inventory data from the foreground system, unlike the other impact categories that also take into account the background processes.

Table 17: Sensitivity analysis for different allocation methods

Allocation Method	CED (MJ)	GWP (kg CO2e)	BRU (t C)	EUT (PO_4-e)
Mass	67,700	9,320	63.7	72
Energy	61,700	5,490	54.1	44.9
Economic	43,800	3,080	15.9	48.7
System Expansion	34,000	2,390	9.60	48.2

The difference between the results for energy and mass are not consistent between the different impact categories is largely explained by the fat content of the materials used and the relative contribution of the blood meal to each category. The reason for this is that when energy allocation is used, a zero value is assigned to the blood meal. As such, there is a significant difference between the results of mass and energy allocation for GWP and EUT since these are highly influenced by the blood meal. For high fat materials, most notably the poultry oil increased when energy allocation is used since fats have almost double the energy content (37kj/g) of protein (17kj/g) or carbohydrates (16kj/g). The impacts of this on the overall results was not significant as this was balanced out by the reduced allocation to the protein based materials, most notably the tuna meal. The only exception is for BRU since this is ultimately a reflection of the fisheries inputs, therefore the decrease in the allocation of burden to the tuna meal far out weights any increase associated with the poultry oil. The degree to which the EUT value varied between the two was also slightly more since the feed was not a major contributor to the impacts for this category. As such the influence of the higher allocation to the high fat salmon guts was more influential on the overall results than the allocation for the feed materials.

As expected, the results for GWP and CED are lower when economic allocation was used due to the high degree of lower-value by-product inclusion. However this is somewhat offset by the additional impacts allocated to the HOG on account of the fact that the economic value of the guts and mortalities is zero, whereas they account for around 15 percent of the total biomass produced by weight. This was of particular influence to the EUT results that were in fact higher because the feeds were only minor contributors to this category, hence the increased allocation to the HOG was much more influential than the reduction in allocation to the various by-products used in the feeds. The largest variation in results was for the system expansion method, which is simply a reflection of the variation in the impacts associated with the by-products used and those for the materials selected as their marginal substitute. The difference was particularly large for the BRU category since the primary cause of this (tuna meal) was substituted with plant-based materials that have but a fraction of the impact for the reasons identified earlier.

6.3.2 Comparison of Functional Units

As can be seen in Table 18, when live weight was used as the FU, the impacts across all categories were lower than for HOG. This is a combination of the additional inputs (mainly energy) for the processing of the fish and the allocation between the primary (HOG) and secondary products (guts and trimmings). Although some analysts prefer live weight as it avoids the need to allocate, the results presented below indicate that in doing so they fail to capture the true costs of production. The results for edible flesh are higher than HOG, which is explained by the fact that a significant amount of the final product sent to market was in the form of HOG, which includes the heads, frames and trims that simply end up as landfill once they reach the market. Since they are not utilised there can be no burden assigned to them. Therefore, when edible product is used as the FU an additional 20 percent (by weight) of the environmental burden is attributed to the edible product, which would be even higher if the impacts associated with the transport to market were also included. Water use has also been excluded from this analysis for the reasons explained earlier.

Table 18: Comparison of results using different functional units

	CED (MJ)	GWP (kg CO2e)	EUT (PO4-e)	BRU (t C)
Per tonne LW	61,800	8,590	66.8	58.6
Per tonne edible flesh	84,300	11,600	89.6	79.3

6.4 Comparison to other production systems

Although direct comparisons between LCA studies are difficult due to the variation in methodology and the associated assumptions made, they help to give perspective to the results obtained. Undertaking such assessments is also necessary if this research is to achieve its goal of identifying methodological issues that need to be addressed if LCA is to be used as a meaningful benchmarking tool. As such, the results from similar salmon LCAs are presented in Table 19, along with the key methodological choices that need to be considered when making comparisons between studies. Only the results for GWP will be compared, since this and CED are the only two impact categories that were common to all four studies. Given that all of these identified a high degree of correlation between these two categories it seems unnecessary to compare both. It is clear from this comparison that the Tasmanian industry has a significantly higher GWP than all other studies, with the greatest variation occurring between the results for the Norwegian industry from Pelletier et al (2009) and the least with that of the UK industry from the same study.

***Table 19*: Results for GWP (t CO_2-e) from LCAs of other salmon production systems**

Country	Allocation	FU	GWP	Source
Norway	Mass	/t edible flesh	2,600	Ytrestøyl, et al., 2011
Norway	Mass	/t edible flesh	2,000	Winther et al. (2009)
Norway	Energy	/t live weight	1,700	Pelletier et al. (2009)
UK	Energy	/t live weight	3,090	Pelletier et al. (2009)
Canada	Energy	/t live weight	2,260	Pelletier et al. (2009)
Chile	Energy	/t live weight	2,160	Pelletier et al. (2009)
Global	Energy	/t live weight	2,040	Pelletier et al. (2009)
Tasmania	Mass	/t HOG	9,320	

In order to make sense of this variation closer consideration of the source of these emissions is required. As can be seen in Table 20 the carbon emissions from the hatcheries (58kg CO_2-e) are similar to all other studies. This is not the case for the marine farms, with emissions per tonne of salmon (506kg CO_2-e) being five times that of Chile, which is the highest of all of the studies (100kg CO_2-e), and almost ten times that of the Norwegian industry (46.2kg CO_2-e) which is the lowest.

It is difficult to determine the exact cause of this from the lack of transparency in the other studies, however discussions with staff from the Tasmanian industry that have previously worked in some of the other industries around the world suggested three reasons that might explain this variation. The first was the additional fuel required to move the significant volumes of water (60KL/t live weight) used for the fresh water bathing from land to the marine farms since this process is not undertaken in any other country. The second was the potential economies of scale associated with the larger production units in these countries that would result in a lower fuel use per tonne. The final suggestion to explain the difference relates to the location of the farms relative to the shore, as a number of the Tasmanian farms, in particular those in Macquarie Harbour require more transport to get to than the on-shore farms that are common in other countries.

Table 20: Comparison of the GWP impacts at the various stages of production

Country	kg CO_2-e				Source
	Total	Smolt	Marine	Feeds	
Norway	2,600	50	50	2,500	Ytrestøyl, et al., 2011
Norway	1,793	46	50	1,700	Pelletier et al. (2009)
UK	3,270	83	92	3,090	Pelletier et al. (2009)
Canada	2,370	36	73	2,260	Pelletier et al. (2009)
Chile	2,300	36	100	2,160	Pelletier et al. (2009)
Global	2,150	46	72	2,040	Pelletier et al. (2009)
Tasmania	***9,150****	***58***	***506***	***8,590***	

Note: study by Winther et al. (2009) omitted due to insufficient data to allow comparisons to be made

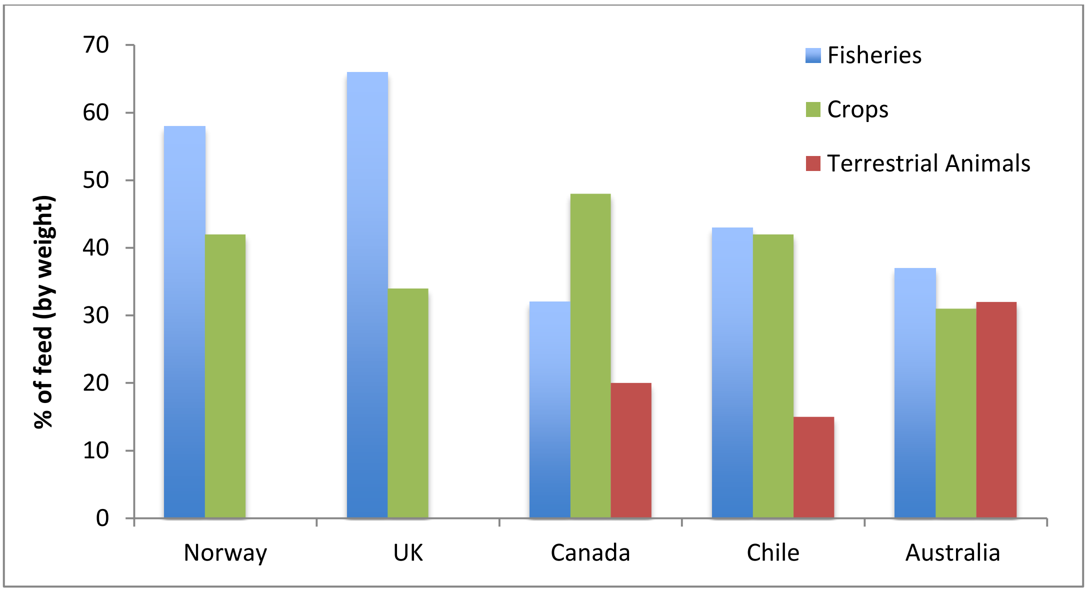
* processing stage not included, therefore total is lower than the amount listed above

However, this source of variation at the marine farming stage of production is insignificant in comparison to the difference in the carbon intensity of the feeds. To determine the major differences that exist between the feeds used in the Tasmanian industry to those from the other countries, a more detailed assessment of the materials used to make the feeds is required. The only one of the above-mentioned studies that was transparent enough to allow for such an analysis to be done was Pelletier et al (2009). The use of similar impact categories between this study and theirs, as well as the global scope of their research made this a good choice for comparisons to be made. As such, data provided in the supporting documentation for their journal article was used to compile a detailed inventory of the inputs used in the feeds for each of the countries, and the associated environmental impacts. A summary of these results can be found in Appendix 16. This was then compared to the results per tonne of feeds from the Tasmanian industry. As was the case for the above assessments of the feeds, for the Tasmanian industry only those that were produced in Australia were analysed since they are the most significant contributor to the overall impacts. When comparing the environmental impacts, the results for the Tasmanian industry presented have been calculated using energy allocation since this is the method used in the study being compared. As such there are some differences in the results presented in the following section and those above where mass allocation was used.

6.4.1 Feed Composition

From the data presented in Figure 27 it is evident that the Tasmanian industry has a much higher inclusion rate of terrestrial animal proteins and oils when compared to the four major salmon producing nations. The Norwegian and UK producers used none on account of the previously mentioned regulations prohibiting the use of these materials, whilst the Chilean and Canadian feeds included 15 and 20 percent respectively, all of which came from poultry by-products. This was in contrast to the Tasmanian industry that used materials sourced from both poultry (30%) and mammalian food production systems (8%).

Figure 27: Comparison of the source of raw materials used in salmon feeds



When comparing the inclusion rate of by-products between the five countries (Table 8), Tasmania was higher (48%) than for all other countries, with the closest being Canada at 36 percent. The other variation to note is the source of these by-products, with Tasmania the only one to include materials from all four of the categories listed, on account of the fact that no other industry used mammalian inputs. In fact, with the exception of Canada that used a combination of crop, fisheries and poultry by-products, all other countries used crops together with either poultry (Chile) or fisheries inputs (UK and Norway). These two factors; the quantity of by-products and the industries from which they are sourced, are highly significant in determining the environmental impacts of the feeds, which is discussed in more detail in the following section.

Table 21: Breakdown purpose-grown and by-products used in global salmon feeds

	Norway	UK	Canada	Chile	Tasmania
Crop (%)	39.2	25.4	39.3	34.8	26
Reduction fishery (%)	52.8	48.2	24.4	43	26
Total Purpose Grown (%)	***92.0***	***73.6***	***63.7***	***77.8***	***52***
Crop by-products (%)	4.6	5.6	9.2	7.9	2
Fisheries by-product (%)	3.5	20.8	7.2	0	8
Poultry by-product (%)	0	0	19.9	14.5	30
Mammalian by-product (%)	0	0	0	0	8
Total by-products (%)	***8.1***	***26.4***	***36.3***	***22.4***	***48***

6.4.2 Environmental Impacts

Before comparisons are made between the feeds it is necessary to highlight some significant differences that exist between the assumptions used by the two studies to model poultry inputs. As can be seen in Table 22, the values used to represent the yields of meal from the offal are 40 percent lower for this study (150kg/ offal compared to 250kg/t in Pelletier et al. (2009), with oil slightly higher at 130kg/t, compared 100kg/t. Since the allocation values are based on the yields, these also varied between the studies. The combination of these factors had a significant impact on the results, in particular GWP and CED on account of the fact that the materials derived from the poultry industry are a major contributor to these impact categories, which is not the case for EUT and BRU. To demonstrate the implications of this, the values used for the GWP of poultry oil and meal from both studies are presented in Table 22, along with the results for this study that have been adjusted using the yields and allocation values used by Pelletier et al.

Table 22: Comparison of assumptions used for poultry by-products (per tonne)

	Poultry Meal	Poultry Fat
Pelletier et al. (2009)		
Yield (kg/t)	260	100
Energy Allocation (%)	60	40
GWP tonne product ($kgCO_2$-e)	3,360	5,280
This Study		
Yield (kg/t)	150	130
Energy Allocation (%)	35	65
GWP per tonne product ($kgCO_2$-e)	3,870	8,380
GWP adjusted for yield	**3,910**	**6,710**

When this adjustment is made, the GWP per tonne of meal is fairly similar since the higher yield offsets the higher allocation rate. This however is not the case for the oil, with the original results from this study being 20 percent higher than the adjusted values. As such, the environmental burden of the poultry oil is 20 percent higher in this study than in Pelletier et al. (2009). The impacts of this on the results are even more significant given that the Tasmanian feeds have a much higher inclusion rate of poultry oil (15%) than the other industries, with Canada the closest at only three percent. These adjustments were done to demonstrate the implications of these differences, and were not used for the assessments in the following sections. There was also significant variation in the values obtained for the feather meal, however there was no data available on the allocation of feathers for Pelletier et al. study, so the reason for this was not able to be assessed. Regardless, the conclusion to be drawn is that the overall results for the poultry inputs are much higher for this study, which needs to be considered when interpreting the following comparisons. Whilst there was a number of other variations that existed between the inventories and assumptions used, this was the only one deemed to be noteworthy. The other thing to note is that as discussed above, the results for blood meal are significantly different when energy allocation is used since a zero value is assigned to the blood. As such, the results presented for energy below are lower than those expressed earlier when mass allocation was used.

The following section will place a particular focus on the quantity and source of the by-products used in the feeds, for as previously mentioned these factors were found to be significant in determining the overall impact of the feeds. This will be done using the method proposed in chapter four, whereby the results for the by-products are presented separately to those for the purpose-grown materials. As previously mentioned, the intention of this approach is intended to provide a balance between the benefits of economic and mass allocation methods. That is the results should be more consistent overtime and enable supply chain risk to be assessed, as is the case for mass allocation whilst still taking into consideration the underlying drivers of production as done by economic allocation.

6.4.2.1 Cumulative Energy Demand and Global Warming Potential

In the examination of the Tasmanian feeds above it was shown that the production of the feed materials was the most significant source of impact for CED and GWP. This however was not the case for all other countries, with Norway, the UK and Chile being around 50 percent compared to over 80 percent in Tasmania and Canada. This was partly due to the fact that the transport and processing stages had higher impacts for these three countries (Table 23), in particular those that had high levels of fisheries inputs, as the data provided indicated that more energy was required to process these materials. Canada and Australia also had lower transportation related impacts, which appears to be related to the fact that majority of the materials used in these countries were sourced locally. It may also have been influenced by the mode of transport used, however data was not available to enable more exact conclusions to be drawn.

Table 23: Comparison of CED and GWP for processing and transport per tonne feed

Country	CED (MJ)		GWP (kg CO_2-e)	
	Processing	Transport	Processing	Transport
Norway	9,070	1,880	412	114
UK	11,000	1,730	623	124
Canada	3,600	612	399	73
Chile	8,710	3,300	473	167
Tasmania	6,540	742	395	93

However this is somewhat insignificant in comparison to the main reason why the production stage contributed a larger percentage to the overall total for Tasmania. This was because the primary production of the feed ingredients used were far more energy intensive than the other countries. This can be seen when the results for this stage of the supply-chain are compared to the other countries, with the results for CED presented in Figure 28 and GWP Figure 29. The variation between the Tasmanian industry and the others is stark, with the total being almost five times that of Chile that had the lowest impacts, and twice the UK that had the highest. If the above-mentioned variation in the values used for the poultry inputs is taken into account, the Tasmanian total decreases by ten percent, however the results are still significantly higher than the others.

When assessing the contribution of by-products compared to purpose-grown materials quite a different conclusion can be drawn. For although the Norwegian industry is the best performer when the total results are used, over 95 percent of this is attributable to materials that were purpose-grown, or in this case caught. This is in contrast to Tasmania that despite being the worst performer overall, however 94% of these impacts were embodied in materials that are derived from a production process driven by demand for another product. The implications of this are discussed in more detail in section 6.7 of this chapter.

Figure 28: Comparison of CED per tonne of feed

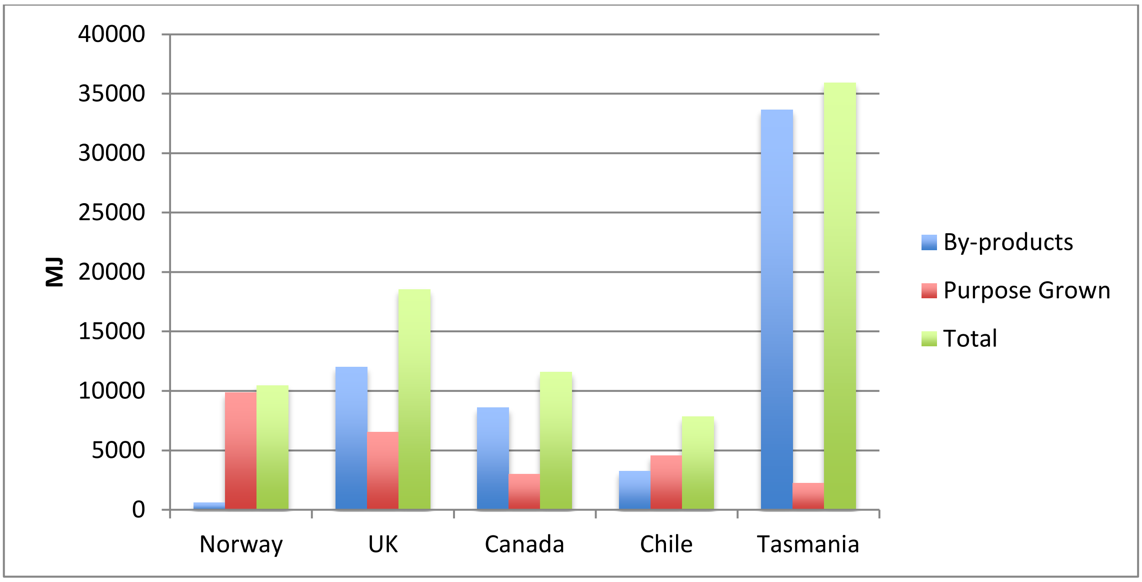
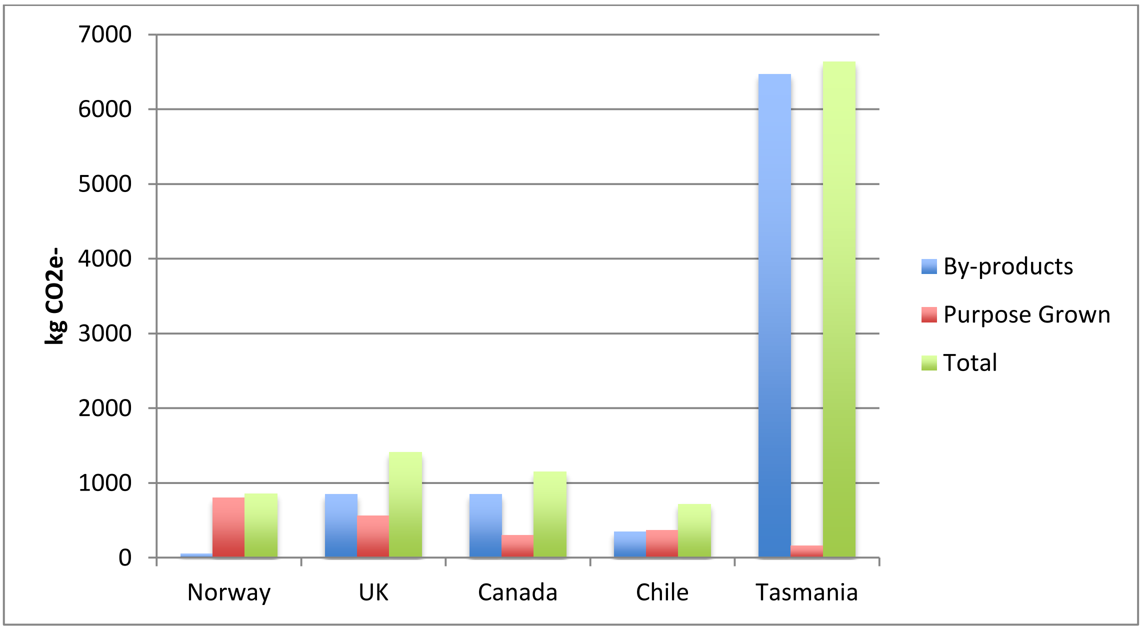


Figure 29: Comparison of GWP per tonne of feed



As noted above, it is not only the amount of by-products that is influential in determining the associated impacts, but more so the source of these materials. For although the UK had a lower use of by-products compared to Chile, the reason for the higher GWP and CED was on account of the inclusion rate of fisheries by-products (20.8%) that came from species that used a large amount of energy in the primary production stage, and subsequently had a high carbon/energy intensity. The reason why the materials sourced from fisheries by-products are more influential than reduction fisheries comes down to the fact that it would not be economic to use species that required large amounts of fuel for reduction purposes as the market would not be willing/able to pay a high enough price to cover these costs. This is in contrast to fish that are caught for direct human consumption that fetch a far higher price which justifies the additional costs to catch them.

To demonstrate this, the carbon intensity of the various fisheries by-products used in the five countries is summarised in Table 24. With the exception of the values presented for the tuna by-products, which have been calculated in this study, all others are taken from the supporting information document for the Pelletier et al. (2009) study. The herring meal and oil were used in all four feed formulations, with the results varying between them. As such, the value presented below is an average of these, whilst the herring silage and whitefish products were only used by one country.

Table 24: Carbon intensity of fisheries by-products per tonne using energy allocation

Fisheries By-products	kg CO_2-e /t
Herring meal*	1,280
Herring oil*	2,570
Herring silage	310
Whitefish meal	5,330
Whitefish oil	9,860
Albacore tuna meal	10,940
Skipjack tuna meal	3,480

* these are averages of the four countries from which herring were sourced in Pelletier et al. (2009)

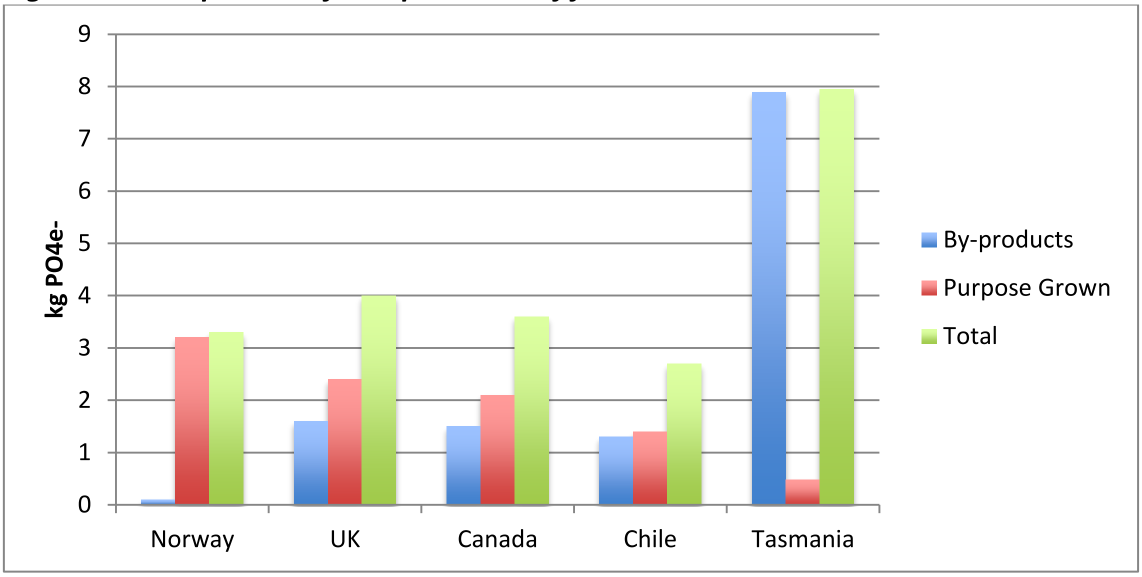
The Chilean industry does not contain any fisheries by-products, and majority of those used in the Norwegian and Canadian industries come from herring, which according to the data presented above has embodied carbon emissions ranging from 310kg CO_2-e/tonne for the silage to 2,570kg CO_2-e /t of oil. This is in contrast to the by-products from whitefish that account for more than half of the fisheries materials used in the UK, with the embodied emissions being 9,860kg CO_2-e/t of meal, and 5,330kg CO_2-e/t oil. The Tasmanian feeds contain seven percent fisheries by-products, which is higher than Canada and Norway, but lower than the UK. However the albacore tuna meal, which is the predominant material used has the highest embodied carbon of all of the above-mentioned species at 10,940kg CO_2-e per tonne. As such, this product that contributes just seven percent of the Tasmanian feeds by weight is responsible for 736 kg CO_2-e, which is more than the total of the Norwegian fisheries products (607kg CO_2-e/t feed) that account for 58 percent of total feed by weight.

As to why Tasmania was so much higher than the UK, the reason is that in addition to using by-products that are from fuel intensive fisheries, unlike the UK they also used significant amounts of poultry by-products (30%) as well as mammalian by-products (8%) that carry a much higher burden relative to crops. To once again put this difference in perspective, the impacts of the blood meal alone (2,740kg CO_2-e) which represented five percent of the Tasmanian feed by weight, contributed 22 times more to the total GWP than all of the crops used in the UK feeds (122kg CO_2-e) which were 31 percent of the weight. These two factors combined with the variation in the assumptions made for the poultry inputs explains why the results for the Tasmanian industry were so much higher.

6.4.2.2 Eutrophication

Tasmania performed much better for EUT than it did in the above-mentioned categories, with the total emissions (72kg PO_4-e/t feed) lower than Canada (74.9kg PO_4-e/t) and higher than the UK (62.7kg PO_4-e/t), Chile (49.3kg PO_4-e/t) Norway (41kg PO_4-e/t). However as previously mentioned, due to the omission of nutrients from the poultry by-products model, this is likely to be an underestimate for the Tasmanian industry. Similar to the findings presented earlier in the chapter, the marine farming stage was the dominant source of EUT impacts for accounting for over 80 percent for the total for all countries. Although the primary production of feed materials was not as influential, when comparing to other countries as shown in Figure 30, not surprisingly the trend was the same as the other impact categories presented above.

Figure 30: Comparison of EUT per tonne of feed



As previously noted, the on-farm emissions are determined by a combination of the digestibility of the feeds and the FCR. Comparing the FCRs for each of the five countries does not help to explain these results (Table 26). The Chilean industry has the highest FCR and one of the lowest EUTs, and conversely Canada and the UK had lower FCRs (1.3) than Australia and Chile (1.4), yet higher EUT.

Table 25: EUT compared to FCR for the different countries

Country	EUT PO_4-e/t feed	FCR
Norway	41	1.1
UK	62.7	1.3
Canada	74.9	1.3
Chile	49.3	1.4
Tasmania	72	1.4

In the absence of any information regarding the digestibility of the feeds, a crude assessment was made based on the expected digestibility of the raw materials used. Recall from chapter three that the use of fats increases the digestibility of the feeds whilst crops often contain anti-nutritional factors that decrease it, in particular those that are not processed. There are also some meals that are more digestible than others, with FM considered to be the most digestible, and feather meal one of the least. To determine if there was any relationship between these materials and the EUT results, the inclusion rates of these four materials in each of the feeds is summarised in Table 26, with the SPC and gluten excluded from the crop-based inputs since the digestibility of these materials is more similar to that of animal proteins than crops. To actually determine the digestibility of the individual feed ingredients and the feeds themselves, it is necessary to undertake tests whereby the materials are fed to the fish and the composition of faecal samples assessed (Belal, 2005). Therefore it is important to note that without this level of detail, the discussion below is nothing more that speculative and intended to provide an insight only.

Table 26: Comparison inclusion rates of materials known to affect feed digestibility

	Total Oil (%)	Fish Meal (%)	Feather Meal (%)	Crop Meals/ Grains/Legumes* (%)
Norway	27.5	35	0	20.8
UK	27.1	45.7	0	19.9
Canada	18.9	20.9	0	32.7
Chile	28.8	25.9	7.2	28.9
Tasmania	24	26	6	20

*excludes gluten and SPC

The above comparison of the feed composition indicates that the countries with a higher inclusion of oils tended to perform better in regards to EUT. There was no clear relationship regarding the fishmeal and crop based inputs, which is likely to be due to the variability of these based on the quality of the raw material and the processing method used. However, when looking closer at which crops are used (Table 27), the Canadian industry that performed significantly worse than the other industries used a lower amount of soymeal and a much higher amount of whole wheat. Since the soymeal has presumably been treated to extract the meal from the oil it would be fair to assume that it had fewer anti-nutritional compounds than the unprocessed wheat. Soy also contains less carbohydrate, more protein content and has a better amino acid profile than wheat, all of which would improve digestibility. However, without more detailed information on the actual digestibility of the different ingredients this cannot be confirmed. Since this information was not provided by the feed companies, a more details investigation was not able to be made.

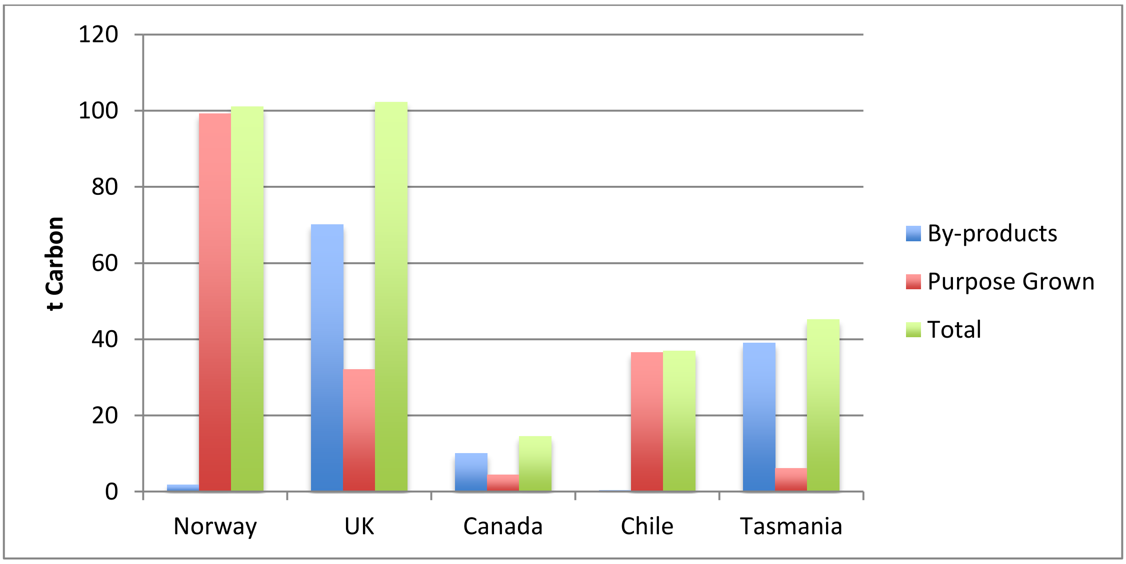
Table 27: Comparison of inclusion rate of whole wheat and soy meal in diets

	Whole Wheat (%)	Soy Meal (%)
Norway	5.5	8
UK	4	8.6
Canada	13.3	4.1
Chile	5.8	9.7
Tasmania	6	0

6.4.2.3 Biotic Resource Use

Since BRU is more or less determined by the amount of fisheries inputs and the trophic level of the species used, it is not surprising that Canada had the lowest BRU, whilst Norway and the UK had the highest. Although the inclusion rates for Tasmania (37%) and Canada (32%) were similar, Tasmania's BRU was almost three times higher on account of the trophic level of the albacore tuna (4.3) compared to that of the herring (3.3), anchoveta (2.7) and menhaden (2.3) used in Canada. As was the case for the other impact categories, the by-products accounted for the majority of the impacts in the Tasmanian industry, as well as the UK that also used a significant amount of fisheries by-products (Figure 31).

Figure 31: Comparison of BRU per tonne of feed



6.4.3 Other Australian Proteins

The other assessment of interest is how the Tasmanian industry compares with other proteins produced within Australia. Table 28 shows the results of recent LCAs undertaken for pork, eggs and chicken all of which adopted a systems expansion approach to deal with allocation. When compared to the results obtained using the same method for the Tasmanian salmon industry, the carbon footprint was almost the same as beef (10,800 kg CO_2-e) more than double that of pork (4,300 kg CO_2-e), four times chicken (2,135kg CO_2-e) and seven times that of eggs (1,300kg CO_2-e). Such a result is very unexpected when considering that salmon have a substantially lower FCR than the other animals, and do not release significant volumes of GHG as it the case for beef cattle.

Table 28: Comparison with other Australian proteins using Mass Allocation

Protein	FU	GWP (kg CO_2-e)	Source
Chicken	/t carcass weight	2,135	Wiedemann, McGahan & Poad (2012)
Eggs	/t eggs	1,300	Weidemann and McGahan (2011)
Pork	/t carcass weight	4,300	Wiedemann et al. (2010)
Beef	/t live weight	10,800*	Ridoutt, Sanguansri & Harper (2011)
Salmon	***Per tonne HOG***	***9,320***	

* average (mean) of the six production systems analysed (min 10,100, max 12,700)

Once again the feeds dominated the impacts for these production systems, but since these studies did not include the same amount of detailed information as the Pelletier et al. (2009) study, it was not possible to assess the portion of the impacts that were attributable to by-products versus purpose grown materials. That said, it is fair to assume that majority of the impacts would come from the latter of these since the feeds used in these studies contained less than five percent by-product.

The other category that was included in the Australian studies that would be interesting to compare is water use. The problem is that the systems boundaries set and the classification systems used vary between these studies, which makes comparisons somewhat meaningless. As such, no attempt will be made to undertaken such an assessment, but rather this is taken as further evidence of the need for clearer guidelines on how to account for water in LCA.

6.5 Salmon By-Products

Whilst significant attention has been given to the consumption of by-products in the Tasmanian feeds, the production of salmon by-products has not yet been addressed. The first source of these is the 1,747 tonnes of sludge produced at the two RAS hatcheries that was used as a soil conditioner on local farms. The other more significant source was the mortalities and processing wastes that collectively accounted for approximately 23 percent of total biomass produced by the industry in 2010-11. As can be seen in Table 29, majority of this material was utilised by other production systems with the exception of 1,820t that was sent to landfill. Seafish are now the major recipient of the by-products (78%), which it transformed into 1,896 tonnes of crude salmon oil of which 850 tonnes was burnt to generate energy for their rendering plant. The remaining 1,050t of oil along with 1,100 t of protein meal were sold to aquafeed companies in Asia. The remaining 50t was protein hydrolysate that was sold as liquid fertiliser.

Table 29: Volumes (tonnes) of by-products produced and their destination

By-Product	Seafish	Pet Food	Compost	Landfill	Total
Mortalities	2,320	0	0	754	3,080
Guts	4,540	0	0	1060	5,600
Heads, frames, trims	2,870	754	114	0	3740
Total	9,730	754	114	1,820	12,400

As discussed in chapter four, the allocation of environmental burden to by-products can be a benefit to those who create them, but a liability to those who use them. This was certainly the case with the results presented in this chapter where-by the high inclusion of by-products in the Tasmanian feeds gave them unfavourable results, however some of this was offset by allocating burden to the mortalities, guts and trims. The disincentive to use by-products is even more exaggerated when LCA is used to assess the impacts of the materials that are derived from the value-adding of salmon by-products. This is because the results for the salmon are already high due to the inclusion of by-products in the feeds, which is made higher by the low yield of the oils and meals relative to the associated raw material. The end result when calculating the impacts of this material using mass allocation is 129,000MJ and 17,600kg CO_2-e per tonne of meal/oil produced by Seafish. Of this, less than two percent is attributable to the actual rendering of these materials. Despite the high embodied environmental impacts in these materials, the nutritional analysis based on the assumptions listed in Appendix 14 showed that the utilization of these materials resulted in a total of 762 tonnes of omega-3s, 300 tonnes of nitrogen and 37 tonnes of phosphorus being returned to the human food system.

6.6 Discussion

The application of LCA to the Tasmanian salmon industry was intended to enable the research questions listed below to be answered.

1. *How can LCA be used to enhance existing efficiency metrics to provide a reliable and comparable assessment of the eco-efficiency of food production systems?*
2. *How does the Tasmanian salmon industry perform when assessed using the proposed methodology?*

More specifically it was intended to address research objectives five and six, which are as follows:

5. *To assess if the proposed modifications achieve the desired result by applying them to an LCA of the Tasmanian salmon industry*
6. *To make recommendations as to how the Tasmanian salmon industry can improve the eco-efficiency of its operations and the associated supply chain*

A discussion of the findings presented above in relation to these objectives will be discussed in the following sections.

6.6.1 Proposed Modifications

As identified in chapter four, one of the most influential decisions that affects the way in which LCA results are interpreted relates to method used to allocate environmental burdens. This was certainly evident in the results of this study, which showed a significant difference when the results using four allocation methods were used. In attempting to determine which is the most suitable, recall that the aim of undertaking this LCA was to provide environmental metrics enable a reliable and comparable measure of eco-efficiency to be made. As stated in chapter one, the intended purpose of this was to assist businesses to make the transition towards eco-efficiency by identifying environmental metrics that can be used alongside financials to set targets, measure performance and evaluate progress. Further to this, it was also identified that this information would also provide governments and third party accreditation schemes with metrics by which they can assess and benchmark different production systems as a way to encourage best practice.

In regards to assessing the eco-efficiency of the supply-chain, the biophysical allocation methods provide the clearest indication of the relative impact intensity of the production processes from which these materials are sourced. However, from a benchmarking perspective, these materials are more likely to carry a higher environmental burden due to the fact that only industries that are geared towards supplying products for direct human consumption can cover the costs associated with these high-energy requirements. In contrast, purpose-grown feed materials need to be cheaper as the feed industry is not willing (or able) to pay the higher price. As such, the results have the potential to be seriously detrimental to industries such as Tasmania's that use significant amounts of by-products from livestock and fisheries production systems. This is even more exaggerated when energy allocation is used since the oils made from the by-products are allocated a higher share of the burden since the energy content of fats is almost double that of proteins and carbohydrates.

Another option is to use economic allocation to minimize the problem described above. However this does not provide a good foundation for benchmarking as the price of these materials varies over time and place, which will influence the subsequent allocation assumptions made. This problem also applies to the ISO preferred option of system expansion as the marginal substitute that is used to model the by-products can change dramatically from year to year based on complex interactions between supply and demand on the global market. The other problem with this method is that the results obtained do not help to identify environmental hotspots, nor do they help to benchmark various feed formulations as it merely states what the impacts would be if the marginal substitute for the by-products were used. Given that the criteria for selecting these substitutes requires that they come from a system that in theory can be expanded to meet growing demand, it is inevitable that the product selected will be crop-based. As such, the results obtained for feeds that are based on by-products from fisheries or poultry will be the same as those based on crops that are purpose-grown which limits the ability to make meaningful comparisons. Conversely, if the tool is used to compare the relative efficiency of herbivorous species such as carp with carnivorous ones such as salmon, the results obtained will fail to capture the differences between the feed requirements of these species. As such, the results would do nothing more than reflect FCR, which would not warrant the time and effort required to undertake and LCA.

This research has suggested another option which is to simply present the results for the by-products separately to those associated with the purpose-grown materials. By doing this, the benefits associated with the biophysical methods can be taken advantage of as producers are still able to see which materials come from impact intensive production systems. However it also provides an additional level of transparency that will enable more informed decisions to be made. For example, take the situation presented in this study whereby the Tasmanian industry performed above average in regards to the well-established forage fish dependency metrics that are used to assess the ecological sustainability of the feeds. The reason for this was that the industry utilised more proteins from fisheries by-products and terrestrial systems. Based on existing measures of productive efficiency, the utilization of these materials is encouraged since it often reduces costs, provides a good balance of nutrients as well as taking pressure off other marine and terrestrial food production systems. As such this practice is widely encouraged by WWF's Salmon Aquaculture Dialogue and the Best Aquaculture Practice (BAP) guidelines as a way to reduce the environmental impacts of feed production. These materials are also seen to be one of most viable solutions to enable the aquaculture industry to escape the fishmeal trap whilst continuing to grow (Tacon, 2010). However, when these metrics are compared those obtained from the LCA, it is clear to see that in the high reliance on these materials in the future could be problematic due to the high embodied impacts.

The scope of the LCA is another issue that needs to be addressed, in particular the choice of FU. As the results presented above indicate, when live weight is used the inputs required to process the fish is not recognised, nor is the treatment of the subsequent by-products that are created. As identified in the above discussion, the way in which the by-products are dealt with can have significant implications for the results obtained. This in turn reduces the ability to make an accurate assessment of the eco-efficiency of production. For example, as demonstrated in this study, the utilisation of the salmon by-products not only reduced the environmental impacts associated with the loss of nutrients to the surrounding environment, it also created an additional value stream. Therefore, it is recommended that LCAs for aquaculture and terrestrial livestock that are seeking to determine the impacts per unit of product should include post-processing within their systems boundaries.

6.6.2 Eco-Efficiency in the Tasmanian Salmon Industry

Starting with the foreground system, it was evident from the comparison between the various salmon industries that Tasmania had a higher than average energy use at the marine farms. Whilst the exact reason for this was not able to be determined due to the level of detail provided by the producers, it is fair to assume that the additional fuel required to tow the 59.3KL/t HOG of freshwater required for the bathing was a contributing factor. Not only would a reduction in this activity improve on-farm fuel efficiency, but it would also reduce their water requirements since this accounted for 90 percent of the total water utilised in the direct production of salmon. Given that AGD is not present on the west coast of Tasmania, it is possible that the expansion at Macquarie Harbour will result in more efficient production since there will be no need for the bathing to take place. That said, this saving might be offset by the need to travel further to reach these farms since they are located further from the shore. As such, it is recommended that producers monitor fuel use for the west coast farms and compare this to determine if there is any gain in fuel efficiency. The other recommendation is for the industry to continue to invest in research focused on solutions to AGD such as selective breeding and vaccinations so as to eliminate the need for bathing to take place all together.

Another strategy to reduce GWP would be to shift from diesel generators used on farm to use more electricity. Whilst this could in theory be achieved by utilising electricity from the grid since the Tasmanian electricity mix is over 70 percent hydro, in reality this would do nothing more than increase total demand, with the additional supply sourced from the Basslink which is predominantly coal fired power. As such the better alternative would be for the producers to implement solar panels or small-scale wind turbines to run some of the on-farm operations, with the grid used as a back up for days when the sun does not provide ample energy. Similarly, these technologies could also be applied to the hatcheries and processing facilities in order to improve the environmental footprint.

In contract to the above-mentioned suggestions that would only yield very small changes to the overall impact of Tasmanian salmon, strategies to address the amount of feed used could potential yield significant gains. For example, the Tasmanian industry performed badly against other industries was FCR, which is a major determinant of environmental and economic costs. To estimate the implications that a reduction in FCR would have on the overall environmental performance of the industry, a scenario analysis has been conducted and the results presented in Table 30. According to these findings, if the industry were to achieve a reduction from their current FCR of 1.4 to the global average of 1.3, this would see an improvement across all impact categories of around 15 percent. If this were to be further improved to the Norwegian average of 1.1, CED, GWP and BRU would improve by around 25 percent, with EUT slightly higher at 31 percent. As previously mentioned, this approach is somewhat limited in that it assumes that the feeds are made of the same blend of ingredients, as such, these findings are to be seen as a rough estimate only. However they do suggest that continued efforts to reduce reduce FCR could be beneficial, so long as the materials used in the feeds do not change significantly. One approach would be to improve the digestibility of the feeds, which would have additional benefits for the associated on farm emissions of nitrogen and phosphorus that are responsible for the EUT. Another would be to loosen the current restrictions on the importation of new genetic broodstock into the Tasmanian industry so as to allow them to utilise salmon that are more efficient convertors of feed to flesh.

Table 30: Sensitivity to changes in FCR, per tonne HOG

FCR	CED (MJ)	GWP (kg CO2e)	BRU (t C)	EUT (PO4-e)
1.4	67,700	9,320	63.7	72
1.3	57,900	7,960	54.1	60.6
1.1	51,000	6,930	47.4	49.7

What would also be useful is to assist feed formulators in developing feeds that are more eco-efficient would be the availability of a database that contained information regarding the environment impacts of the raw materials used to make the feeds. Such a tool could be used to complement the existing economic and nutritional data that feed producers use to assist them in formulating commercially viable feeds and allow for the trade-offs between these variables to be better understood. A crude example based on the findings from this study is presented in Table 31. In addition to the information provided here, it would also be useful if data pertaining to the digestibility of the materials could also be included since this is a key determinant of EUT.

Such a database is also vital if LCA is to be used as a benchmarking tool, for as highlighted by the example provided above regarding the poultry inputs, small variations in the assumptions made can have significant impacts on the subsequent results. Similar issues have been identified in regards to commonly used feed ingredients such as palm oil and soy whereby the decision to include the GHG emissions associated with land clearing that often accompanies plantations of these materials can have significant implications on the results (Ziegler et al., in press). This issue has been flagged as a priority area by a group of organisations that represent feed manufacturers that have recently formed a partnership with the FAO to improve the environmental impacts of the livestock industry. As one of their priorities, this group that is comprised of organisations such as the International Feed Industry Federation (IFIF), American Feed Industry Association (AFIA) and the European Compound Feed Manufacturers' Federation (FEFAC) have pledged to work together with the FAO to establish methodologies and databases that ensure there is an even playing field for LCAs undertaken for feeds (FAO, 2012e). However, until this has been accomplished, it is vital that care is taken when attempting to compare studies.

Whilst some might argue that adding environmental requirements to the already arduous task of formulating feeds that have to meet economic, nutritional and functional criteria, this research has made it clear that this is not an additional requirement, but one that is synonymous to future costs. Based on the laws of supply and demand, the cost of energy and nutrients is going to increase in the future, so too are the emissions that represent losses of these to the surrounding environment. Therefore accounting for these impacts will be essential if the food system and the businesses within it are to become more eco-efficient.

The final suggestion relates to the form in which the final product is sent to market. Over 70 percent of the salmon harvested is sent as HOG of which approximately 34 percent by weight is non-edible material that will be sent to landfill. If this was to be filleted prior to being sent to market not only would there be a reduction in the waste sent to landfill in the urban centres where the fish are sold, but it would also allow for this material to be collected in a centralised location where it can be value-added. This would not only reduce the percentage of burden allocated to the fillets (Winter et al., 2009), but the reduction in the weight being transported to market would also minimise the transportation costs and the associated emissions created in the process. Since waste treatment was not included in the scope of this study, these comments are only speculative. In making this recommendation it is also recognised that such a strategy may not be possible on account of the associated food safety and food preservation considerations. Although such an assessment is outside the scope of this study, it seems worthy of further exploration to determine if there are packaging or storage solutions that could address these issues whilst not creating another set of more detrimental impacts in the process.

Table 31: Example of decision-making tool to assist feed formulators in developing feeds

Feed Ingredient	Cost ($)	Energy (MJ)	Crude Protein (kg)	Omega 3 (kg)	GWP (kg CO_2-e)	CED (MJ)	BRU (t C)	EUT (kg PO_4-eq)
Peruvian fishmeal	1583	19100	670	29.8	532	8310	25.9	0.13
Albacore Tuna meal	not available	19100	550	39.7	10900	158000	658	1.1
Skipjack Tuna Meal	not available	19100	550	39.7	3480	50400	141	0.88
Feather meal	654	22600	800	2.3	6050	62800	3.3	7.45
Poultry meal	935	19900	650	2.8	6110	63800	4.7	7.58
Blood meal	920	19700	850	0	54800	93800	26.5	72.9
Meat meal	575	17200	500	3.2	42400	71600	12.3	54.3
Lupins	301	13600	380	2	566	5810	0.64	1.06
Fava bean	297	16500	260	0.5	438	3990	0.53	2.87
Wheat	130	12100	100	0	246	3060	0.41	1.21
Soya Protein Concentrate	623	15200	620	0.6	639	6920	0.48	2.18
Fish oil	1200	39700	0	344	516	8070	12.9	0.13
Poultry oil	905	39700	0	23	5400	52500	3.5	6.2

6.7 Assessing the Implications on Sustainable Consumption

An assessment of sustainability would not be complete without giving consideration to the implications of the production decisions on matters pertaining to consumption. As described in chapter three, salmon is widely promoted as a nutritious product most notably due to its high omega-3 FA content. Since salmon are not able to produce these nutrients endogenously, it is essential that they be provided via their feeds, with pelagic fish such as anchoveta being the best source. This begs the question as to what impact the shift towards replacing FO with non-marine oils has had on the nutritional value of the fish. Interestingly, samples of Tasmanian salmon collected by scientists at CSIRO indicate that this shift in the composition of the diet has decreased the omega-3 content of the flesh by 30-60% (Nichols and Turchini, 2010). However, it is the still well above 60mg of EPA and DHA per 100g threshold set by the Australian Food Standards Code (FSANZ, 2012) to be classed as a good source of omega 3. In fact, it is still the highest of all species sold in Australia (Nichols and Turchini, 2010).

In fact it is arguable that this shift from marine to terrestrial oils has not only helped to improve the productive efficiency of the salmon industry, but also the allocative efficiency by making this healthy food more accessible to the Australian population. This relates to the fact that the feeds represent 60 to 70 percent of the total cost to produce salmon and as such are influential on the price paid by the consumer. As can be seen in Table 31, the price of FO ($1,205) is approximately 30 percent higher than the price of poultry oil ($905). This difference is even greater when looking at the variation between FM ($1,583) and other high quality proteins such as poultry meal ($935) and SPC ($623). Therefore it is fair to assume that these savings, together with the various achievements described in chapter three have played a role in the ten percent reduction in the market price of salmon over the past five years (Ryan, 2012).

Another solution that holds promise is the adoption of GM crops discussed in chapter three that are designed to produce their own EPA and DHA. This would improve the eco-efficiency of the salmon feeds, for as shown in Table 31 the crop inputs had the lowest impact of all the feed ingredients. It would also significantly help to relieve pressure on wild-capture fisheries to provide these essential nutrients. This would simultaneously improve the nutritional quality of the salmon as it would contain more of the EFAs that have been shown to play a role in the prevention and treatment of a range of common health conditions. Such a recommendation is based on the premise that these materials did not incur other health and environmental problems, and that the costs to produce them did not make them unaffordable. Therefore, in order for this to be a viable alternative, rigorous testing would be needed to satisfy the authorities of the production of these materials was safe for the natural environment, and that their consumption did not pose any risks to human health. This would need to be accompanied by consumer education campaigns that highlight the health and environmental benefits so as to overcome the current negative perception of GM foods.

6.8 In Summary

The above assessment provides some interesting insights into the sustainability of production and consumption within the Tasmanian salmon industry, as well as identifying areas that need to be addressed to improve the eco-efficiency of production. A summary of these, together with recommendations for the future will be provided in the following chapter, as well as an overview of the LCA tool and its ability to drive the food system towards a more sustainable future.

Chapter 7: Conclusion

Food producers are under increasing pressure to provide for a growing population that is demanding good quality, nutritious foods. At the same time, they face significant supply-side constraints as the cost of the inputs required to produce food reach record highs. Similarly, the ongoing misuse of ecosystem goods and services has led to a decline in the productive capacity of the global food system, with eutrophication, desertification and changing weather patterns amongst the numerous issues that are making the task of producing food even more challenging. To address this conflict between the needs and wants of society and the biophysical constraints of the earth it is essential that the efficiency of production be improved. However, unlike the productivity gains that have been characteristic of the previous half a century, the future will require a more balanced approach that looks beyond purely economic objectives such as yield, throughput and profits to give more consideration to environmental implications.

In the search of a suitable tool to enable this form of efficiency to be measured, this research drew on the expertise from three diverse yet interrelated disciplines – environmental science, nutritional science and economics – under the universal banner of sustainability science to find answers to the following research questions:

1. *How can LCA be used to enhance existing efficiency metrics to provide a reliable and comparable assessment of the eco-efficiency of food production systems?*
2. *How does the Tasmanian salmon industry perform when assessed using the proposed methodology?*

Six objectives were devised to guide this research in its quest to find answers to these questions. These are presented below, followed by a summary of the findings to demonstrate how these objectives have been met.

1. *Identify key stakeholders from the Tasmanian salmon industry and the inputs, outputs and processes involved in the associated supply chain (chapter 2)*
2. *Evaluate current measures used to assess productive efficiency of salmon aquaculture (chapter 3)*
3. *Assess the pros and cons of using LCA as a tool to provide the environmental data required to make an assessment of eco-efficiency (chapter 4)*
4. *Make recommendations as to how the LCA methodology can be modified to provide more reliable and comparable data (chapter 5)*
5. *To assess if the proposed modifications achieve the desired result by applying them to an LCA of the Tasmanian salmon industry*
6. *To make recommendations as to how the Tasmanian salmon industry can improve the eco-efficiency of its operations and the associated supply chain*

The overview of the Tasmanian salmon industry in chapter two identified the major stakeholders and production processes that make up the supply chain. This was followed by a discussion of the historic events that led to the development FCR and FIFO ratios that are commonly used to assess the productive efficiency of salmon production and other aquaculture species. It was identified that although these had provided a meaningful yardstick against which the success of various technological, biological and nutritional advancements were measured in the past, they were limited in their ability to address the problems identified in chapter one. The reason for this was the failure to account for:

1. The utilisation of industrial energy
2. The utilisation of nutrients and energy contained in by-products
3. The trade-offs between the various measures of sustainability

It was acknowledged that LCA provided a suitable framework to address the above-mentioned limitations, although there were a number of methodological issues that prevented this from providing a reliable and comparable assessment of food systems. The most problematic is the selection of allocation method, with the pros and cons of the three methods recommended by the ISO guidelines discussed in chapter four. It was determined from this that mass allocation was the most appropriate since it offered a stable measure that did not discriminate against the inclusion of high fat feed ingredients. However, the major drawback was the way in which environmental burden was allocated to by-products. To overcome this issue, this research proposed an alternative method, whereby the results of the LCA for the by-product are presented separately to those for the purpose-grown materials.

To determine if this suggestion provided a feasible solution to the allocation problem, it was incorporated into the LCA methodology used to assess the Tasmanian salmon industry. The results obtained provided the additional transparency required to assess the eco-efficiency of the production system and the supporting supply chain. This was particularly beneficial when comparing the results of this study with those from other salmon LCAs as it enabled the results to be put into context, and was also useful when comparing the results to other efficiency measures such as FCR and FIFO. The environmental data obtained from this assessment was then able to nutritional and economic variables as it enabled more informed decisions to be made regarding the most appropriate feed formulation from an eco-efficiency perspective.

The sensitivity analyses undertaken in chapter six indicated that there was significant variation in the results when different functional units and allocation methods were used. This highlighted the need for further guidance on the LCA methodology if it is to be used to assess the eco-efficiency in aquaculture, as is the case for third party certification schemes such as ASC and SEAT. Recommendations as to which approach should be used for aquaculture and other intensive animal production are summarised in Table 32, accompanied by a rationale as to why these have been chosen. In addition to identifying the need to set clearer guidelines, it was also suggested that a database that contains LCA information for commonly used feed ingredients be developed. This would not only help in allowing meaningful comparisons to be made between studies, it would also enable feed producers to give thorough consideration to eco-efficiency when formulating feeds.

Table 32: Recommendations regarding key methodological decisions for LCAs used for assessing animal production systems

Issue	Recommendation	Rationale
Functional unit and scope	Specify carcass weight (HOG) or edible product to be used as FU to include post-processing in the scope	• These ensure that the by-products that are created are accounted for • Allows for more meaningful assessment of where energy, nutrients and value are lost from the production system
Allocation method	Specify mass allocation to be used as primary method	• Provides a stable measure for benchmarking purposes since it does not vary over time and place • Provides a good insight into the impact intensity of the production processes associated within a supply chain • Doesn't discriminate against high fat materials

The assessment of the Tasmanian salmon industry revealed a number of areas where there energy, nutrients and value were lost from their supply chain. These are summarised in Table 33, along with recommendations as to how to improve their performance in the future. A number of these relate to areas that require further research for it is not only through *answering* questions that progress is made, but also through *raising* them (Hundloe, 1985).

Table 33: Recommendations to improve the efficiency of Tasmanian salmon industry

Issue	Recommendation	Rationale
Feed conversion ratio	Continue to invest in research and development to improve FCR	• FCR is major determinant of environmental and economic impacts, therefore a reduction will improve performance across a range of sustainability measures

Digestibility of feeds	Improve the digestibility of the feeds	• Digestibility is major determinant of FCR and EUT, therefore will result in better performance
Genetic stock	Laws regarding the importation of new genetic stock to be relaxed	• The current stock used in Tasmania is not ideal for commercial purposes • Enabling new stock could potentially help to improve FCR and resistance to AGD amongst other factors.
Amoebic Gill Disease	Continue with research to develop alternative treatment for AGD	• Freshwater bathing responsible for the majority of water use • Significant amounts of fuel also used to tow the water • Elimination/reduction in need to undertake this activity will reduce reliance on these resources and the associated environmental impacts
Renewable energy	Investigate costs and benefits of implementing renewable energy at the various production sites	• Could help to reduce the costs of production • Will minimise CED and GWP
Logistics to market	Investigate the costs and benefits of transporting salmon to market as fillets instead of HOG	• The additional weight increases fuel use and associated transportation cost • The heads, frames and trims sent to market as part of HOG go to landfill • If collected and treated in centralised location there would be a reduction in the loss of energy, nutrient and value form the system
On-going monitoring	Producers to monitor their use of energy,	• To enable progress to be measured

	feeds and water as well as the nutritional composition of feeds and the salmon	
GM crops	Continue research into the feasibility of GM crops that are able to synthesize DHA and EPA	• Environmental impacts for crops were relatively low • Would take pressure off finite fisheries resources • Would enable improved health outcomes for society as these nutrients would be more readily available in the diet

In summary, this research provided some practical suggestions as to how the LCA methodology could be modified to provide reliable and comparable data to assess the eco-efficiency of food production. The feasibility of applying these modifications was demonstrated through the application of the proposed methodology to the Tasmanian salmon industry. Since feeds were the major driver of all measures of efficiency, it is fair to conclude that the findings of this research are applicable to other intensive animal production systems.

The findings of such an assessment are able to be used alongside existing measures of productive efficiency to provide a comprehensive assessment that will enable the food system to meet the coming challenges. This will not only help to ensure that the businesses within the food system are more aware and accountable for the outcomes of their decisions, but it will also help to bridge the growing gap between supply and demand for food. As demonstrated by this research, no single discipline is going to solve a problem of this magnitude, but rather expertise from a diversity of areas is needed, of which environmental science, nutritional science and economics are paramount.

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Appendix 1: Life Cycle Assessment Literature Review Matrix

Bibliographic Info	Goal and Scope	Impact Categories & LCIA Method	Allocation Methods Used	Software
SALMON				
Aubin, J., Papatryphon, E., van der Werf, H. and Chatzifotis (2009) Assessment of the environmental impact of carnivorous finfish production systems using life cycle assessment, Journal of Cleaner Production 17 (2009) 354-361	• To characterize the environmental impacts of 3 diff production systems for carnivorous finfish species in Europe • Functional unit = 1 tonne of live weight fish • Included infrastructure and equipment • Waste not included • Location: Europe	• EUT, ACD, GWP, BRU (NPP), CED, water dependence • Uses interesting calculations used to determine the localised eutrophication	• Attributional LCA • No mention of allocation method used	Simapro
Ayer, N and Tyedmers, P (2009) Assessing alternative aquaculture technologies: LCA of salmon culture systems in Canada, Journal of Cleaner Production 17 (2009), 362-373	• To quantify and compare the potential LCA impacts associated with producing salmon using 4 different culture systems in Canada • Functional unit = 1 tonne of harvest ready live-weight fish • Solid fish wastes from the recirculation hatchery were accounted for • Location: Canada	• ABD, GWP, HTP, MTP, ACD, EUT, CED • Calculated CED using method v 1.03 • No mention of impact Ax method used	• Attributional LCA • Co-products at the feed production stage allocated according to nutritional energy content • Expansion of systems boundaries were applied on farm, the market products and waste	Simapro
Boissy, J., Aubin, J., Drissi, A., van der Werf, H.,Bell, G. and Kaushik, S. (2011) Environmental impacts of plant-based salmonid diets at feed and farm scales, *Aquaculture 321, 61-70*	• To determine the environmental consequences of replacing FM and FO with plant-based sources in salmonid feeds • FU = one salmonid feeds and one tonne of live weight • Waste not included • Location: feed ingredients taken from all over the world, salmonid production in France and Scotland	• CED, Water use, land use, NPP, Terrestrial ecotoxicology, GWP, EUT, ACD	• Attributional LCA • Economic allocation	Simapro
Ellingsen, H. and Aanondsen, A. (2006) Environmental impacts of wild caught cod and farmed salmon – A comparison with chicken, *Int J LCA* 1 (1) 60-65 2006	• To find reference level for environmental performance by comparing LCAs of Norwegian cod fishing and salmon farming and compare these with chicken farming • Waste not included • FU: 0.2 kg fillets – corresponds to usual serve size • Location: Norway	• BRU, land use, CEU, anti-fouling impacts, as well as over-fishing and disturbance of the sea floor on qualitative basis • Eco-indicator 99	• No mention of methodological approach • Mass allocation used for cod, and economic allocation for chicken and salmon	Simapro
Hall, S., Delaporte, A., Phillips, M., Beveridge, M. and O'Keefe, M. (2011) *Blue Frontiers: Managing the Environmental Costs of Aquaculture*, The WorldFish Center, Penang, Malaysia.	• To compare and contrast the global and regional environmental demands of aquaculture for a range of biophysical resources across the dominant aquaculture species and to compare these to other animal protein production • Systems boundaries: infrastructure, seed production, packaging and processing, transport not included • FU: overall production per species (t), per country (t), Location: Global	• EUT, ACD, GWP, BRU, CED, land occupation • CML baseline used for EUT, ACD, GWP • Ecoinvent used for CEU	• Attributional LCA • No mention of allocation	Simapro

Papatryphon, E., Petit, J., Kaushik, S. and van der WerfSource, H. (2004) Environmental Impact Assessment of Salmonoid Feeds Using Life Cycle Assessment, Ambio, Vol. 33, 6, pp. 316-323	• To assess the environmental impacts associated with 4 different salmonoid feeds • Functional unit = feed required to produce one tonne (t) of rainbow trout • Feed being analysed = "energy and nutrient dense" (40% crude protein, 26% fat, 19.5 kJ g-' digestible energy) - also known as "low pollution" extruded feeds • Waste not included	• CED, NPP, GWP, ACD, EUT • Normalisation step was undertaken using CML to compare with global per capita impacts	• Attributional LCA • Economic allocation • Normalisation stage also done - relative units: calculated environmental impacts divided by the respective global annual per capita impacts	Simapro
Pelletier, N. and Tyedmers, P. (2007) Feeding farmed salmon: Is organic better, Aquaculture 272 (2007) 399-416	• To evaluate the comparative environmental performance of conventional and organic feeds (4 feeds used) • Used multiple functional units = 1 tonne of feed ingredients, 1 tonne of feed, 1 tonne of salmon • Waste not included • Location: Canada	• ACD, EUT, GWP, MTP, CED, BRU • CML Baseline 2000 method used for impact Ax • Calculated CED using v1.03 • BRU calculated based on carbon content (NPP)	• Attributional LCA • Gross nutritional energy • Sensitivity analysis conducted for economic allocation (significant differences) and mass allocation (insignificant difference)	Simapro
Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., & ...Silverman, H. (2009). Not all salmon are created equally. *Environ. Sci. Technol., 43*(23), 8730-8736	• To determine the resource use and environmental impacts of salmon in each of the 4 major production areas as well as a weighted global average • Functional unit = one live-weight tonne of farmed salmon • Waste not included • Location: Norway, Canada, Chile and UK	• CED, BRU, GWP, ACD, EUT • CED calculated using CED method (see refs for details) • BRU calculated using NPP • All other impacts calculated using CML 2 Baseline	• Attributional LCA • Gross chemical energy content • Also conducted sensitivity analysis for a range of other methodological choices – look at article for details	Simapro
Winther, U., Ziegler, F., Hognes, E., Emanuelsson, A., Sund, V. and Ellingsen, H. (2009), *Carbon footprint and energy use of Norwegian seafood products*, SINEF Fisheries and Aquaculture	• To quantify carbon footprint and energy use related to a selection of Norwegian seafood products (including salmon) • FU = one kilo of edible product transported to the wholesaler • Waste not included • Location: Norway	• GHG emissions, CED	• Attributional LCA • Mass allocation	Simapro
Ytestøyl, T., Aas, T., Berge, G., Hatlen, B., Sørensen, M., Ruyter, B., Thomassen, M. et al. (2011) Resource utilisation and eco-efficiency of Norwegian salmon farming, NOFIMA Report 53/2011	• To calculate the carbon footprint and area used to produce one kilo of Norwegian salmon that is fed different diets • FU = one kilo edible product at farm gate • Waste included • Location: Norway	• Carbon footprint, occupation of agricultural land, sea primary-production-required • ReCiPe 2010 used for carbon footprint	• Attributional LCA • Mass allocation	Simapro

AUSTRALIAN INTENSIVE ANIMAL PRODUCTION LCA

Eady, S., Viner, J. and MacDonnell, J. (2011) On-farm greenhouse gas emissions and water use: case studies in the Queensland beef industry, *Animal Production Science* (51) 667-681	• To benchmark the GHG emissions and water use for two production systems • FU = 1 kg liveweight • Location: Australia	• GWP, water use • Beef GHG calculator (Eckard, 2010) and FarmGAS (Australian Farm Institute) used to estimate direct emissions, with NGGI used for indirect	• Attributional LCA • Economic allocation	Simapro
Peters, G., Rowley, H., Wiedemann, S., Tucker, R, Short, M. and Schulz, M (2010) Red meat production in Australia: Life cycle assessment and comparison with overseas study, *Environ. Sci. Technol.*, 44 (4) 1327-1332	• To assess the carbon footprint and energy use for three supply chains (beef and sheep) in three different regions of Australia over two years and compare this to overseas beef • FU =1kg carcass weight, 1ha of land used for production • Location: Australia	• CED, GWP • NGGI emissions factors used to calculate GWP	• Hybrid EIO-LCA, process based LCA used to assess foreground system with EIO-LCA for the extended supply chain • Mixture of economic and mass allocation used to deal with co-products	Not mentioned in article
Ridoutt, B., Sanguansri, P. and Harper,G. (2011) Comparing carbon and water footprints for beef production in southern Australia, *Sustainability* (3) 2443-2455	• To calculate the carbon and water footprints for six diverse beef cattle production systems in southern Australia • FU = 1kg liveweight • Location: Six regions in southern Australia	• GWP, water use • Water Stress Index (Pfister et al., 2009) used for water, IPCC for GWP	• Attributional LCA • Economic allocation	Not mentioned in article
Weidemann, S. and McGahan, E. (2011) Environmental assessment of an egg production supply chain using life cycle assessment, AECL Publication No 1FS091A	• Six goals that reflect various stakeholder interests relating to the production of caged and free range eggs • FU = 1 kg of eggs ready for retail distribution • Manure and spent hens included • Location: Australia	• CED, GWP and water usage • IPCC model used for GWP • ABS and Owens (2002) used to assess water usage	• Attributional LCA • Systems expansion used to deal with co-products • Economic allocation used as alternative for sensitivity analysis	Simapro
Wiedemann, S., McGahan, E., Grist, S. and Grant, T. (2010) Environmental Assessment of Two Pork Supply Chains Using Life Cycle Assessment, RIRDC Publication No. 09/176 RIRDC; Canberra	• Four goals that reflect various stakeholder interests relating to measuring the environmental impacts and resource usage of two alternate management systems and geographical regions • FU = 1 live piglet/weaner at farm gate, 1 live slaughter pig at farm gate, 1 kilo of hot standards carcass weight at abattoir gate • Manure included, processing off-cuts and viscera not • Location: Australia	• CED, GWP and water usage • NGGI emissions factors used to calculate GWP • ABS water use and water footprinting approach taken to account for water use • Mass balance approach used to determine nutrient flows for manure	• Attributional LCA • Systems expansion used to deal with co-products	Simapro
Weidemann, S., McGahan, E. and Poad, G. (2012) *Using life cycle assessment to quantify the environmental impact of chicken meat production*, RIRDC Publication No. 12/029, RIRDC; Canberra	• Seven goals that reflect various stakeholder interests relating to different production systems (conventional and free range) in two geographic locations (Queensland and South Australia) • FU = 1 kilo live weight at farm gate, 1 kg chilled, whole chicken at processor gate • Manure and offal etc. included • Location: Australia	• CED, GWP and water use • DCCEE and IPCC models used to calculate GWP • ABS water use and consumptive freshwater use models used • Mass balance approach used to determine nutrient flows for manure	• Attributional LCA • Systems expansion used to deal with co-products	Simapro

Appendix 2: Questionnaire used to collect primary data

a. **Salmon Producer Questionnaire**

Hatchery – Production Data for 2010-11 Financial Year

Street Address: ____

Feed Usage for the 2010-11 Financial Year

Feeds

Feed Type	Volume (t)	Cost ($)
Skretting		
Ridleys		
Other (please specify)		

Average FCR for the 2010-11 Financial Year

Lifecycle Stage	eFCR	bFCR
Freshwater		

Production Data

	Volume (tonnes)
Standing biomass (1st July, 2010)	
Biomass inputs (smolt)	
Biomass harvested	
Closing biomass (31st June, 2011)	
Mortalities	

Sales Volumes – see production sheet provided

Product	Volume (t)
Smolts	

Energy Use

Source	Quantity	Unit	$
Electricity (from grid)			
Diesel (for electricity)			
Diesel (vehicles)			

Best Available Estimate of Water Use

Source	Use	Volume In	Volume Out

Waste

Volume/weight of waste sent to landfill for 2010-11 financial year:

____

____

Additional Data

Please note any circumstances that have affected production during the 2010-11 financial year that would impact on the representativeness of these values in terms of being an ‘average’ year.

Marine Operations

Feed Usage for the 2010-11 Financial Year

Feed Type	Total Volume (t)	Cost ($)
Skretting Feeds		
Ridleys feeds		
Other (please specify)		

Production Data for 2010-11 Financial Year

	Volume (tonnes)
Standing biomass (1st July, 2010)	
Biomass inputs (smolt)	
Biomass harvested	
Closing biomass (31st June, 2011)	
Mortalities	

Average FCR for the 2010-11 Financial Year

Lifecycle Stage	bFCR	eFCR
Saltwater		

Other Farm Inputs

Energy

Source	Quantity	Unit
Electricity (from grid)		
Natural gas (please specify if LPG or LNG)		
Diesel		
Other (please specify)____________________		
Other (please specify)____________________		

Transportation for the 2010-11 Financial Year

Feed

From___________________ to the farm at ___________________

Truck Type/Size	Total Volume Transported (t/annum)	Avg. Load (t)	No. loads/annum	Fuel Use (L/load)

Smolt

From___________________ to the farm at ___________________

Truck Type/Size	Total Volume Transported (t/annum)	Avg. Load (t)	No. loads/annum	Fuel Use (L/load)

From____________________ to the farm at ______________________

Truck Type/Size	Total Volume Transported (t/annum)	Avg. Load (t)	No. loads/annum	Fuel Use (L/load)

Fish for Processing

From farm at _______________ to processing plant at _____________________

Truck Type/Size	Total Volume Transported (t/annum)	Avg. Load (t)	No. loads/annum	Fuel Use (L/load)

Additional Data

Please note any circumstances that have affected production during the 2010-11 financial year that would impact on the representativeness of these values in terms of being an 'average' year.

____

____

____

____

____

Processing Plant – 2010/11 Financial Year

Street Address: ____

Quantity of By-Products

Part of Fish	% of Whole Fish
Fillet	
Head	
Frames	
Skin	
Blood	

Destination of By-Products

Destination	Volume (t)		
	Heads & Frames	**Guts**	**Rejects**
Pet Food company			
Compost			
Seafish			
Other________________			

Solid Waste (excluding above mentioned by-products)

Volume/weight of waste sent to landfill for 2010-11 financial year:

____

Brief description of composition waste (i.e. organic matter, plastics, cardboard)

____

Details of Quality and Quantity of Products

What % of total throughput (tonnes) from factory is salmonids?________________%

Product	Volume (t)	Market Value ($)
HOG		
Fillets		
Value Added		
Other _________________		
Other _________________		
Other _________________		

Nutritional Information

	Average Nutritional Composition (per 100g)			
Product	Protein (g)	Energy (kJ)	Omega-3 (mg)	Phosphorus (mg)
Salmon				
Trout				

Additional Data

Please note any circumstances that have affected production during the 2010-11 financial year that would impact on the representativeness of these values in terms of being an 'average' year.

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b. Feed Producer Questionnaire

Transportation Summary

Please provide the details of the origins of each of the raw materials (country if overseas and state if from Australia) and the capacity of the containers used for the various transportation stages. If the product is sourced from more than one source (i.e. fish meal sourced from Peru and Thailand), please list these separately.

Raw Material	Origin	Avg. Volume of Container (t)			% Total Land Travel by Road
		Ship	Road	Rail	

Energy, Water and Waste

Energy Usage at Mill

Energy Usage by Source for 2010-11 financial year

Source	Quantity	Unit
Electricity from public grid (low voltage)		
Electricity from public grid (high voltage)		
LPG (plant)		
LPG (forklifts) – rough estimate satisfactory		
Total Output for 2010-11 (t):		

Water Usage at Mill

Water Usage at Mill for 2010-11 financial year

Source	Use	Volume In	Volume Out

Briefly describe the wastewater treatment system in place:

____

____

____

Waste

Volume/weight of waste sent to landfill for 2010-11 financial year:

____

Brief description of composition waste (i.e. organic matter, plastics, cardboard)

Production Weighted Feed Composition

Please list the major feed ingredients and provide the production-weighted inclusion rate of each ingredient in one tonne of the nominated feeds. Do not include micro additions, vitamins, minerals or attractants.

Huon Products

Ingredient	Standard local Freshwater	Standard local Saltwater	Imported Freshwater	Imported Saltwater

Petuna Products

Ingredient	Standard local Freshwater	Standard local Saltwater	Imported Freshwater	Imported Saltwater

Tassal Products

Ingredient	Standard local Freshwater	Standard local Saltwater	Imported Freshwater	Imported Saltwater

Van Diemen Products

Ingredient	Standard local Freshwater	Standard local Saltwater	Imported Freshwater	Imported Saltwater

Please provide a short summary of the methodology used to determine the production weighting of the various feeds.

____

____

____

____

Appendix 3: Assumptions used to calculate measures of forage fish dependency for Tasmanian and global salmon production

a. FIFO Ratio (Tacon and Metian, 2008)

Variables	Tasmanian	Global
eFCR	1.42	1.25
Total FM (t)	16153	461500
FM reduction efficiency (kg/t)	22.5	22.5
Pelagic equivalents FM (t)	71791	2051111
FoFM	3590	102556
Total FO (t)	5060	307700
Additional FO (t)	1470	205144
Additional pelagic FO (t)	29409	4102889
Total Pelagic Required (t)	101200	6154000
Total salmon produced (t)	52985	1538000
FIFO	1.91	4.00

b. FIFO Ratio (Naylor, 2009)

Variables	Tasmanian	Global
eFCR	1.42	1.25
Diet FM (g/kg)	23.00	24.00
FM reduction efficiency (g/kg)	22.5	22.50
Diet FO (g/kg)	7	16.00
FoFM (kg/kg)	8.00	8.00
RFE (fm)	1.45	1.33
RFE (AO)	0.80	2.09
FIFO	2.25	3.43

c. FIFO Ratio (Jackson, 2009)

	Tasmania	Global
eFCR	1.42	1.25
Level of FM in diet	23	24.00
Level FO in diet	7	16.00
Yield FM from wild fish	22.5	22.50
Yield FO from wild fish	5.00	5.00
FIFO	1.55	1.82

d. FFDR (WWF, 2012)

Variables	Tasmanian	Global
eFCR	1.42	1.25
% FM in feed from forage fish	16.5	18
% FO in feed from forage fish	7	12
Conversion factor (meal to live weight)	22.5	22.5
Conversion factor (oil to live weight)	5	5
FFDRm	1.04	1.00
FFDRo	1.99	3.00

e. MNDR (Crampton et al., 2010)

Variables	Tasmanian	Global
eFCR	1.42	1.25
FoFeed (%)	7	16
Fmfeed (%)	23	24
FoFM (%)	0.08	0.08
PrFM (%)	68	68
OilSalm (%)	13	19.7
PrtSalm (%)	21	17.5
MODR	0.97	1.14
MPDR	1.06	1.17

Appendix 4: Assumptions made and source of data used for biophysical and economic allocation

Chicken Allocation	Mass (%)	Energy (%)	Economic (%)	Notes and References
Edible meat	55	54	90	Mass data from V. Kite (pers comm). Fillet energy value ACMF (2011), remaining energy from feed data, economic estimated*
Offal and bones	35	38	10	
Feathers	10	8	0	
Poultry meal	54	35	50	Mass data from B. Hopkins (pers comm), energy and economic values taken from data provided by feed companies
Poultry oil	46	65	50	
Mammalian Allocation				
Meat	35	79	36	Mass data from MLA (2002), energy based on Atwater factors, and economic values taken from Index Mundi (2013)
Offal	5	6	6	
Blood	2	0	2	
Rendering material	50	2	54	
Hide	8	13	2	
Meat Meal	62	44	90	Mass data from MLA (2002), energy based on Atwater factors, and economic values taken from Index Mundi (2013) and feed data
Tallow	38	56	10	
Crop Allocation	% Mass	% Energy	Economic (%)	Notes and References
Canola meal	48	27	30	Mass based on Australian avg, adjusted for moisture (Seberry et al., 2010), energy calculated using Atwater factors, economic based on global average World Bank (2012a)
Canola oil	52	73	70	
Soybean meal	80	65	65	Mass based on Pelletier (2006), energy calculated using Atwater factors, economic based on global average World Bank (2012a)
Soybean oil	20	35	35	
Lupin kernel	75	80	80	Mass and energy based on Pulse WA (2011), economic values taken from data provided by feed companies
Lupin hull	25	20	20	
Wheat gluten	13	25	10	Mass based on US Trade Commission (1998), energy taken from NRC (2011), economic estimated
Wheat starch and fibre	87	75	90	

Fisheries Allocation	% Mass	% Energy	Economic (%)	Notes and References
Tuna fillet	64	49	90	Mass based on yields (Duangpaseuth et al., n.d), energy derived from USDA (2012), economic estimated*
Tuna trimmings	36	51	10	
NZ Hoki fillet	60	60	90	Mass based on Sydney Fish Market (2012), nutritional composition assumed to be the same for fillet and offal, economic estimated*
NZ trimmings	40	40	10	
Anchoveta meal	85	60	70	Mass based on yields (Winther et al., 2009), energy taken from data provided by feed companies, economic Pelletier (2006),
Anchoveta oil	15	40	30	
Tuna meal	88	76	70	Mass based on yields (Duangpaseuth et al., n.d), energy from data provided by feed companies, economic assumed same as anchovetta
Tuna oil	12	24	30	
Salmon Allocation	**% Mass**	**% Energy**	**Economic %**	**Notes and References**
Live weight	94	94	100	Mass and economic from Tassal data, energy using Atwatter factors
Mortalities	6	6	0	
HOG	90	84	100	Mass and economic from Tassal data, energy using Atwater factors
Viscera	10	16	0	

System Expansion Model

Primary Product	By-Product/s	Marginal Product	Justification for Marginal Product
Canola oil	Canola meal	Lupins	Similar protein content, with no need to allocate to oil
Soy meal	Soy oil	Palm oil	Palm oil is the marginal oil used by the market (not for salmon)
Chicken meat	Protein meals and oil	Canola seed	Ratio oil and meal for poultry by-products is similar to canola (55:45)
Fish fillets	Trimmings	Soy	Marginal protein with similar protein content

* No data available, so conservative estimate made based on data for salmon

Appendix 5: Production-weighted average used to model salmon production taken from data provided by salmon and feed companies

a. Inventory for one tonne smolt (hatcheries)

Inputs	Units	Amount
Feeds		
Australian made feeds	t	0.7
Imported Feeds	t	0.5
Feed Transport (road)	tkm	894
Feed Transport (ship)	tkm	11426
Energy		
Electricity	MWh	8.7
Diesel	l	34.7
Water		
Surface or groundwater	KL	86.2
Outputs	**Units**	**Amount**
Nutrient Losses		
Total N	kg	27.2
Total P	kg	7.3
Nutrients in Sludge		
Total N	kg	5.4
Total P	kg	2.1
Mortalities	kg	147.8

b. Inventory for one tonne live weight salmon (marine farms)

Inputs	Units	Amount
Biomass		
Smolt (0.13kg)	kg	30
Smolt transport	tkm	53
Feed		
Local feeds	t	1.2
Imported feeds	t	0.2
Feed Transport (road)	tkm	1286

Feed Transport (ship)	tkm	4714
Energy		
Electricity	kWh	103
Diesel	l	58.5
Petrol	l	22.1
Water		
Water from dam	KL	57.8
Outputs	**Units**	**Amount**
Nutrient Losses		
Total N	kg	65
Total P	kg	9.9
Mortalities	kg	57.4

c. Inventory per one tonne HOG (processing)

Inputs	**Units**	**Amount**
Biomass		
Liveweight salmon	t	1.2
Harvest transport	tkm	218
Energy		
Electricity	kwh	91.2
Diesel	l	0.08
Water		
Reticulated supply	KL	1.76
Outputs	**Units**	**Amount**
Nutrient Losses		
Total N	kg	0.14
Total P	kg	0.01
Water		
Waste water to treatment	KL	1.63

Appendix 6: Estimation of nutrient load from feed at FCR 1.4

	Nitrogen	Phosphorus
Feed Composition (%) [a]	6.72	1.1
Digestibility (%)	85[a]	50[b]
Amt Digested (%)	5.7	0.55
Particulate losses (%)[c]	1.02	0.55
Carcass Composition (%) [d]	2.99	0.5
Retained growth 1.4 FCR (%)[e]	2.14	0.4
Dissolved nutrient losses (%)[f]	3.56	0.2
Total losses (%)	4.58	0.71

[a] values derived from average feed for the Tasmanian industry

[b] Buschmann et al., 2007

[c] Total consumed minus the amount digested, the remainder assumed to be lost as particulate in faeces

[d] Stead and Laird, 2002

[e] FCR based on Tasmanian industry average of 1.4.

f Difference between the amount digested and the amount retained in carcass, which is equivalent to soluble losses from metabolic by-products and excess to physiological requirements

Appendix 7: Production-weighted feed

Feed Ingredient	% Inclusion
Crops	***28***
Wheat	6
Dehulled lupins	5
Faba bean	9
Wheat gluten meal	2
Soya Protein Concentrate	6
Fisheries	***34***
Anchovetta meal	18
Anchovetta oil	8
Albacore Tuna by-product meal	7
Skipjack Tuna by-product meal	1
Poultry	***30***
Feather meal	6
Poulty meal	9
Poultry oil	15
Mammalian	***8***
Blood meal	5
Meat meal	3

Appendix 8: Source of data for modelling primary production and processing of crops

Feed Ingredient	Raw Material Production	Processing	Notes
Wheat	Gross margin budget (Vic, Qld)	n/a	
Lupins	Gross margin budget (NSW, WA)	AusLCI	Assumed to be the same as soybean processing
Faba beans	Gross margin budget (NSW)	Ecoinvent	Swiss processing data modified for Australian energy mix
Wheat gluten (Australia)	Gross margin budget (Qld)	Cederberg, 1998	Processing assumed to be the same processing as corn gluten
Wheat gluten (China)	Gross margin budget (Qld)	Cederberg, 1998	Assumed to be same as Australia with electricity mix modified for China
Soy protein concentrate	Ecoinvent	Apaiah, 2006	Production data from Brazil, processing assumed to be the same as pea protein

Appendix 9: On-farm input and output per hectare of crops grown

Input	Lupins	Wheat	Faba Bean
Yield (t/ha)	1.2	2.8	1.5
Inputs			
Seed (kg)	100	100	100
Glyphosate (L)	6.40	4.8	7.2
Urea 46% N (kg)	-	120.0	-
MAP 11% N, 22% P (kg)	-	90.0	100
Superphosphate 8% P, 11% S (kg)	100	-	-
Total Nitrogen (kg N)	0	65.1	11
Total Phosphorus (kg P)	8	19.8	22.0
Diesel for tractor (L)	10	40.0	11.5
Transport to and from Farm			
Rigid truck inputs to farm (100km) (tkm)	13.04	24	13.72
Artic. Truck to grain storage (100km) (t/km based on yield)	120	280	150
On-Farm Emissions to Water from Fertiliser			
Nitrate (kg/ha)	0	18.8	0
Phosphate (kg/ha)	0.320	0.728	1.582
On-Farm Emissions to Air			
N2O (from fertiliser application) (kg/ha)	0.729	0.647	0.990

Source: DAFF, 2012; NSW DPI, 2012; WA Department of Agriculture, 2005

Appendix 10: Emissions Factors Used to Calculate GHG Emissions from fertiliser application used for Australian-grown crops

Emissions to Air	Emissions Factor
N_2O emissions directly from soil	0.003
NH_3 emissions from soil	0.1
N_2O emissions indirectly through NH_3	0.01
N_2O emissions from N in crop residues	0.0125
Fraction of N available for leaching and run-off	0

Source: DCCEE, 2012b

Appendix 11: Assumptions used to Model Poultry By-Products

(Source: Weidemann, McGahan and Poad, 2012)

a. *Feed Ration*

Inputs	Queensland (kg/t)	Southern States (kg/t)
Sorghum	428	0
Barley	0	139
Wheat	211	530
Soybean meal	167	158
Canola	24.5	35
Other protein meal	28	0
Other pulse meal	26	50
Animal by-product meal	0	39
Oil	26	23

Note: The inventory used to model these crops can be found in Wiedemann et al., 2009

b. *Feed Milling (/t feed)*

Energy Inputs	Per t feed
Electricity (kWh)	19
LPG (l)	0.02
Natural gas (m3)	4.8

c. *Breeding (/1t live weight)*

Inputs	Per t LW
Feed ration (kg)	423
Electricity (kWh)	144
LPG (l)	7.8
Diesel (l)	0.4
Petrol (l)	0.4
Outputs[a]	
Manure N excretion (kg)	6.9
Manure P excretion (kg)	2.3[b]
Manure VS excretion (kg)	61,9

[a] As noted in text, this were not included in the Simapro inventory but were used to make estimation of the additional EUT potential

[b] Estimated using formula from NPI (2012)

d. Grow-out

Inputs	Per t LW
Feed ration (kg)	1,853
Electricity (kWh)	402.5
LPG (l)	92.6
Diesel (l)	26.5
Petrol (l)	1.6
Outputs[a]	
Manure N excretion (kg)	31.3
Manure P excretion (kg)	10.6[b]
Manure VS excretion (kg)	348
Total N2O-N emissions	0.91

[a] As noted in text, this were not included in the Simapro inventory but were used to make estimation of the additional EUT potential
[b] Estimated using formula from NPI (2012)

e. Meat processing

Inputs	
Electricity (kWh)	155
LPG (l)	7.7
Natural gas (m^3)	6.6
Diesel (l)	0.2

f. Rendering (per tonne of offal)

Inputs	Amount	Source of Data
Electricity	48.4 kWh	ARA, 2011
Outputs	**Amount**	**Source of Data**
POM	150kg	B. Hopkins, pers comm
Poultry oil	130kg	B Hopkins, pers comm

g. Rendering (per tonne of feathers)

Inputs	Amount	Source of Data
Electricity	48.4 kWh	ARA, 2011
Outputs	**Amount**	**Source of Data**
Feather meal	280kg	B Hopkins, pers comm

Appendix 12: Assumptions used to Model Mammalian By-Products

a. ***Beef cattle system characteristics*** (average of inventory for inland weaners and north coast weaners presented in Ridoutt et al., 2011)

Pasture land use	
Unimproved pastures (ha yr^{-1})	313
Non-irrigated improved pasture (ha yr^{-1})	48.5
Livestock	
Cows at time of mating (head)	100
Age of cows at first calf (month)	30
Calves (head yr^{-1})	74
Replacement heifers (head yr^{-1})	20
Replacement bulls (head yr^{-1})	3
Mortality and culls (head yr^{-1})	1
Animals sold to feedlot ot market, excl culls (head yr^{-1})	21
Feed	
Fodder crops (ha yr^{-1})	6.5
Grain (t yr^{-1})	4.2
Hay (t yr^{-1})	2.4
Fuel for pasture maintenance (kL yr^{-1})	0.9
Fertiliser for pasture maintenance (t yr^{-1})	2.6
Feedlot subsystem	
Initial weight (kg head yr^{-1})	380
Final live weight (kg head yr^{-1})	585
Days in feedlot (days $head^{-1}$)	115
Electricity (MJ head-1 day^{-1})	0.813
Natural gas (MJ head-1 day^{-1})	1.300
Diesel (MJ head-1 day^{-1})	1.138
Feedlot ration (kg head-1 day^{-1})	11.8

b. Biogenic GHG emissions calculated by FarmGas (2013)

Gases	t/head	kg/t LW
Methane (enteric)	0.08	0.1
Methane (wastes)	0.014	0.0
Total methane (CH4)	*0.094*	*0.2*
Nitrous oxide (N2O) from manure and urine	0.001	0.0
Total converted to CO2-e	***2.284***	***3.9***

c. Feedlot ration

Feedlot Ration	Kg/t
Wheat	500
Barley	200
Sorghum	100
Grass silage	200

d. Rendering (per tonne offal)

Inputs	Amount	Source of Data
Electricity	48.4Wh	ARA, 2011
Outputs	**Amount**	**Source of Data**
Meat meal	180kg	MLA, 2002

e. Rendering (per tonne blood)

Inputs	Amount	Source of Data
Electricity	48.4Wh	ARA, 2011
Outputs	**Amount**	**Source of Data**
Blood meal	167kg	MLA, 2002

Appendix 13: Energy Use for Fisheries

a. Diesel used for fishing (per tonne landed)

Fish	Country	Diesel Use (l)	Source of Data
Anchoveta	Peru	19	Winther et al., 2009
Skipjack Tuna	Thailand	349	Tyedmers and Parker, 2012
Albacore Tuna	Samoa	1135	Tyedmers and Parker, 2012

b. Rendering of anchoveta (per tonne wet weight)

Inputs	Amount	Source of Data
Heavy fuel oil (for reduction)	30l	Winther et al., 2009
Outputs	**Amount**	**Source of Data**
Anchoveta meal	220kg	Winther et al., 2009
Anchoveta oil	40kg	Winther et al., 2009

c. Rendering of tuna by-products (per tonne wet weight)

Inputs	Amount	Source of Data
Heat from N. Gas	1331 MJ	DEFRA, 2007
Heavy fuel oil	40.8 kWh	DEFRA, 2007
Outputs	**Amount**	**Source of Data**
Tuna meal	350kg	Duangpaseuth et al., n.d
Tuna oil	50kg	Duangpaseuth et al., n.d

Appendix 14: Assumptions used to calculate nutrients recovered from salmon processing waste

By-product	Viscera	Heads & Frames	Whole Fish/ Mortalities
% live weight fish[a]	10	27	100
Protein content[b] (%)	22[c]	12	18.7
Total Lipid[d] (%)	37	25	14
Omega-3 content[d] (%)	10.2	0.86	5
Phosphorus content[e] (%)	0.35	0.35	0.35
Energy[f] (MJ)	13.7	9.3	7.8

[a] based on industry average (pers comm Peter Bennett), 2% blood loss not accounted for

[b] Ramirez (2007)

[c] Assumed to be the same as salmon flesh, average of Tassal and HAC nutritional information

[d] Mooney et al. (2002)

[e] Based on the phosphorus content of whole salmon taken from Ytrestoyl et al., 2011

[f] For flesh this was based on average of Tassal and HAC nutrition information, for all others it was calculated using Atwater factors for fat and protein

Appendix 15: Trophic level used to calculate BRU

Species	Trophic Level
Anchoveta	2.7
Tuna (Albacore)	4.3
Tuna (Skipjack)	3.8

Source: Fishbase, 2010

Appendix 16: Breakdown of impacts (per tonne feed) from the production of by-products and purpose grown materials for five salmon industries (results for all industries other than Tasmania taken from Pelletier et al., 2009)

Norway	CED (MJ/t)	BRU (t C/t)	GWP (kgCO2/t)	EUT (kg PO4-e/t)
Crops	1989.8	0.188	228	1.7
Crop by-products	188.2	0.024	24.5	0.1
Dedicated Reduction Fisheries	7882.8	98.968	577.1	1.5
Fisheries by-products	406.1	1.832	30.1	0
Poultry by-products	0	0	0	0
Mammalian by-products	0	0	0	0
Total	***10466.9***	***101.0***	***859.7***	***3.3***
Amt from by-products	***594.3***	***1.856***	***54.6***	***0.1***
Amt from purpose grown	***9872.6***	***99.156***	***805.1***	***3.2***
UK				
Crops	918.4	0.107	97.4	0.8
Crop by-products	174.6	0.03	24.4	0.1
Dedicated Reduction Fisheries	5604.6	32.053	462.8	1.6
Fisheries by-products	11838.4	70.047	827.8	1.5
Poultry by-products	0	0	0	0
Mammalian by-products	0	0	0	0
Total	***18536***	***102.2***	***1412.4***	***4***
Amt from by-products	***12013***	***70.077***	***852.2***	***1.6***
Amt from purpose grown	***6523***	***32.16***	***560.2***	***2.4***
Canada				
Crops	1589.1	0.19	197.2	1.9
Crop by-products	238.8	0.05	34.8	0.2
Dedicated Reduction Fisheries	1422.3	4.298	105.1	0.2
Fisheries by-products	2671.2	9.387	197.4	0.5
Poultry by-products	5684.6	0.579	616	0.8
Mammalian by-products	0	0	0	0
Total	***11606***	***14.5***	***1150.5***	***3.6***
Amt from by-products	***8594.6***	***10.016***	***848.2***	***1.5***

Amt from purpose grown	***3011.4***	***4.5***	***302.3***	***2.1***
Chile	CED (MJ/t)	BRU (t C/t)	GWP (kgCO2/t)	EUT (kg PO4-e/t)
Crops	1207	0.16	119.2	0.8
Crop by-products	213	0.043	30.5	0.1
Dedicated Reduction Fisheries	3364.7	36.337	248.7	0.6
Fisheries by-products	0	0	0	0
Poultry by-products	3040	0.344	319.9	1.2
Mammalian by-products	0	0	0	0
Total	***7824.7***	***36.9***	***718.3***	***2.7***
Amt from by-products	***3253***	***0.4***	***350.4***	***1.3***
Amt from purpose grown	***4571.7***	***36.5***	***367.9***	***1.4***
Tasmania				
Crops	1031	0.124	106.0	0.45
Crop by-products	66	0.011	5	0.03
Dedicated Reduction Fisheries	847	6.05	59.0	0.03
Fisheries by-products	11087	36.1	767.0	0.09
Poultry by-products	18210	1.17	1690.0	2.1
Mammalian by-products	6500	1.71	4010.00	5.3
Total	***37741***	***45.2***	***6637***	***7.95***
Amt from by-products	***35863***	***39.0***	***6472.0***	***7.9***
Amt from purpose grown	***1878***	***6.17***	***165.0***	***0.5***